THE LEWISIAN ROCKS OF THE ISLAND OF TIREE, INNER HEBRIDES

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THE LEWISIAN ROCKS OF THE ISLAND OF TIREE, INNER HEBRIDES

being a thesis presented by

IAIN GLEN LAMOND SINCLAIR

to the University of St. Andrews
in application for the degree of
Doctor of Philosophy.

CERTIFICATE

I certify that IAIN G.L. SINCLAIR has been engaged in research for twelve terms at the University of St. Andrews, that he has fulfilled the conditions of Ordinance No. 16, and that he is qualified to submit the accompanying thesis in application for the degree of Doctor of Philosophy.

I certify that the following thesis is based on the results of research carried out by me, that it is my own composition, and that it has not previously been presented for a higher degree.

CAREER

In 1952 I matriculated at the University of Edinburgh and in 1956 obtained the degree of B.Sc. with second class honours in geology.

From 1956 until 1960 I worked as an exploration geologist in Canada, initially in Labrador with the Iron Ore Company of Canada, and latterly in British Columbia with Pacific Petroleums Ltd.

I returned to Scotland in August, 1960 and commenced research work on the Lewisian rocks of the Island of Tiree.

SUMMARY OF INVESTIGATIONS AND CONCLUSIONS.

The research work presented in this thesis was undertaken to determine the nature and the relationships of the rocks which make up the Lewisian Complex on the Island of Tiree, and to attempt to interpret their metamorphic history. The rocks have been mapped and some 250 thin-sections examined in the laboratory. Twenty-one chemical analyses have been executed using rapid techniques. The mineral assemblages within the rocks have been classified according to the metamorphic facies principle of Eskola as modified by Fyfe, Turner and Verhoogen (1958).

The complex has been found to consist predominantly of migmatites but there also occur some bodies of fairly homogeneous intermediate, basic and ultrabasic gneiss. The general outlines of these bodies are generally more or less conformable with the trend of the banding in the enclosing migmatite.

The commonest type of migmatite is a light to medium grey, generally well banded rock, the principal mafic components of which are hornblende and biotite. It is designated the Banded Migmatite. Two other varieties, the Massive Migmatite and the Contorted Migmatite, occur in lesser amounts. The Massive Migmatite contains varying amounts of clinopyroxene and orthopyroxene in addition to some hornblende and minor biotite; banding within it is generally weakly developed and sometimes completely absent. The Contorted Migmatite has a streaky rather than banded appearance and irregular contortions and crenulations are common within it. The principal

mafic component of this phase of the migmatite is biotite and, at one locality, it also contains varying amounts of orthopyroxene and garnet. The mineral assemblage in the Banded Migmatite is indicative of crystallization in the upper amphibolite facies and that in the Massive Migmatite suggests lower granulite facies. The presence of both orthopyroxene and biotite in the Contorted Migmatite indicates that the assemblage in that phase is one transitional between the amphibolite and the granulite facies and that equilibrium was probably not attained within it during metamorphism.

Throughout the migmatite mass there occur 'resister' (Read, 1957) bands and lenses of basic, ultrabasic and metasedimentary rock. These bodies of 'resister' rock are in almost all cases extended parallel to the banding of the enclosing migmatite. Concordant and transgressive veins and bands of acid pegmatite are common and 'resister' bands are often penetrated and disrupted by pegmatitic material. The 'resister' bands appear, therefore, to have been in a much more brittle condition during migmatitization than was the enclosing rock. The mineral assemblages within the broader 'resister' bands are often suggestive of crystallization under lower granulite facies conditions but in the narrower bands and lenses and in the marginal zones of the broad bands, amphibolite facies assemblages occur; chemical analyses suggest that the mineralogical transformations in the 'resister' bands were essentially isochemical. A series of analyses between the centre and the margin of a large ultrabasic lens reveal that its marginal zone is richer in silica, lime, alumina and alkalies and poorer in magnesia and iron oxides, compared with its interior. The contamination of the marginal zone is considered to have taken place during the migmatitization of the enclosing rocks when fluids were available to facilitate diffusion. Isoclinal folds with axial planes parallel to the banding of the migmatite occur in occasional basic lenses. Their presence demonstrates that the palaeosome had been folded prior to migmatitization and that the same stress system probably prevailed during both these processes.

Textural evidence, although not conclusive, suggests that in the broad basic 'resistor' bands the pyroxene has, at least in part, formed at the expense of pre-existent hornblende. Furthermore, there is no textural evidence, such as the rimming of pyroxene grains by amphibole, to suggest that the amphibolite assemblages in the marginal zones of these bands have formed by diaphthoresis of a granulite facies assemblage. Replacement of pyroxene by amphibole in response to an easing of pressure and temperature conditions or to an influx of volatiles is a commonly observed phenomenon in many areas. The opposite process, which is postulated to have taken place in these basic bands, has less often been demonstrated. However, Groves (1935) considered that the clinopyroxene and orthopyroxene in the charnockitic rocks of Uganda were formed from amphibole in response to increase in temperature and pressure. More recently, Quensel (1951), Compton (1957) and Parras (1958) have invoked this process to explain the petrogenesis of charnockitic rocks in Sweden, the United States and Finland respectively. Parras, indeed, has said that the petrogenetic key to the formation of charnockites is "the production of pyroxenes and garnet at the expense of or in lieu of hornblende." In certain of the metasedimentary bands, on the other hand, mantling of diopside grains by colourless amphibole is commonly observed and diaphthoretic replacement of pyroxene by amphibole has almost certainly taken place. The suggestion that pyroxene has formed at the expense of hornblende in the basic bands while evidence can be observed that the opposite process has apparently taken place in the metasedimentary bands, may appear inconsistent. However, this apparent contradiction is believed to be due to variations in the availability of water during metamorphism, a topic which is more fully discussed below.

The mineral assemblages in the more or less homogeneous bodies of intermediate, basic and ultrabasic gneiss, mentioned above, are variable. The intermediate gneiss which makes up the northerly trending ridge of Ben Hough contains an assemblage typical of the lower granulite facies, and petrographically it resembles the intermediate charnockites of the classical Indian localities. The uniformity of this rock mass and its chemical composition suggest that it may have originated as a dioritic igneous mass. The basic gneiss of Balephetrish Hill also appears to have crystallized under lower granulite facies conditions while the basic gneiss at Balephuil and Salum Bay contains assemblages suggestive of the amphibolite facies. No positive evidence as to the origin of these basic gneisses has been observed. The assemblages in the interiors of the bodies of ultrabasic gneiss at Ceann a Mhara and along the west coast of the island are lower granulite facies types; transitions to amphibolite facies assemblages are found close to the margins of these bodies. Certain textural features of these ultrabasic gneisses, together with their chemical composition, suggest that they may have originated as ultrabasic igneous rocks.

Apparent differences in metamorphic grade therefore exist amongst the various rock types which make up the Lewisian Complex of Tiree. There are two possible explanations for these differences. Either a period of granulite facies metamorphism may have affected the whole rock mass and have been followed by a period of selective retrogressive metamorphism; or there may have been only one main period of metamorphism and the apparent differences in metamorphic grade may be reflections of the differences in the availability of water in different portions of the rock mass during that period. The first of these explanations has been used to explain the co-existence of granulite facies and amphibolite facies assemblages in adjacent rocks in several areas (Dearnley, 1962), but in the present case it is considered that the second explanation is more likely to be the true one. The main evidence in favour of this postulate is discussed below.

Several workers including Read (1957), Turner (1958), Yoder (1955) and Reynolds and Frederickson (1962) have recently discussed the important influence which the presence or absence of water may have on the mineral assemblage produced within a rock during metamorphism. All of these workers consider that mineral assemblages of apparently different metamorphic grade can be produced in adjacent rock masses, undergoing simultaneous metamorphism under the same conditions of temperature and pressure, if there are significant differences in the amount of water within them. Thus it is possible to have the production of 'dry' granulite facies assemblages and 'wet' amphibolite facies assemblages in adjacent bands of rock during the same period of metamorphism.

The rock types which occur most frequently in the metasedimentary bands within the migmatite mass are marble and calc-silicate rock accompanied by occasional bands of quartzite and granulite. In a geosynclinal sedimentary pile the sediments which have been metamorphosed to give these types would be accompanied by large amounts of shales and greywackes; therefore it seems feasible to suggest that the migmatites are, at least in part, the product of the metamorphism and migmatitisation of such sediments. Shales and greywackes are relatively water-rich rocks and, before metamorphites containing granulite facies assemblages could be produced from them, large amounts of water would have to be expelled. Subsequent diaphthoresis of granulite facies assemblages to those typical of the amphibolite facies would require re-introduction of large amounts of water and other volatiles. Therefore to maintain the theory that a period of high grade 'dry' metamorphism affected all of the rocks and was followed by a period of 'wet' retrogressive metamorphism, it is necessary to postulate that a large scale expulsion of water and volatiles was followed at a later period by a re-introduction of similar material. However, if it is considered that the rocks have undergone only one main period of metamorphism a somewhat simpler pattern of events can be postulated; namely, that the whole mass was lowered to a level in the crust where pressures and temperatures were high enough to promote the genesis of granulite facies minerals in the 'resister' bands but that the passage of water up through the initially water-rich shales and greywackes caused 'wet' amphibolite assemblages to develop in them.

If the entire rock mass had, in fact, been subjected to widespread granulite facies metamorphism followed by selective diaphthoresis then it would be reasonable to expect to find abundant textural evidence in the migmatites of the retrogressive phase. In South Harris (Davidson, 1943), for example, coronae of kelyphite around garnet grains and the complete mantling of pyroxene grains by hornblende are common features in the basic gneisses which have undergone diaphthoresis after the main period of metamorphism. In the rocks of Tiree, however, such features are almost entirely absent and indeed, in the basic resister bands, the pyroxene appears to have formed at the expense of the hornblende. It was mentioned above that mantling of diopside grains by amphibole can be observed in some of the bands of metasediments. That does not, however, invalidate the general contention that there was not any period of widespread retrogressive metamorphism. According to Bowen (1948), diffusion of heat is a faster process than the diffusion of ions and molecules; it is possible, therefore, that in occasional bands, pyroxenes would be generated and later partially amphibolized by the action of migrating fluids.

On the whole, therefore, although perhaps it might be possible to interpret the available evidence somewhat differently, the writer considers that only one main period of metamorphism has affected these rocks. Although there was probably some local diaphthoresis during the easing of conditions at the close of this period, it is not accepted that there was any large scale conversion of granulite facies assemblages to amphibolite assemblages. The almost complete lack of textural indications of amphibolization of pyroxene in the migmatites and 'resister' bands, although negative evidence, is considered to indicate that this interpretation is the correct one.

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PART I

INTRODUCTION

INTRODUCTION.

The Island of Tiree.

The Island of Tiree, the outermost member of the Inner Hebrides group, lies some twenty miles west of Mull. Its length from north-east to south-west is twelve miles, its breadth varies from three-quarters of a mile to six miles and it has an area of approximately thirty square miles. The flatness of its topography make it a somewhat unique member of the Inner Hebridean group of islands. Only three hills are over two hundred feet in height and they are all located in the broader western half of the island, while in the eastern half at only two points does the elevation exceed one hundred feet. Most of Tiree, therefore, is rather flat and featureless and large areas are covered by dunes of blown sand, especially in the very flat central portion of the island where the Reef airfield is located, or by raised-beach deposits. Inland exposures are often sparse and are absent altogether in the areas of blown sand; but exposures along the coastline are generally good, except for the gaps caused by the existence of several fine beaches, the largest of which, Traigh Mhor, is over two miles long. Plate 1 illustrates the general flatness of the Tiree landscape.

PLATE 1.

A. View from Ben Gott across the flat-lying central portion of the island, The Reef. In the distance can be seen Ben Hough (388'), a ridge made up of intermediate charnockitic gneiss.

B. View east-north-east from the summit of Ben Hough. The agricultural land in the foreground is flat raised-beach terrain. Loch Bhasapoll can be seen in the middle distance and beyond it Balephetrish Bay.

PLATE 1.

A.

B.

Previous Investigations.

In 1789 the notorious German adventurer, Rudolf Erich Raspe, who is said to have combined the professions of poet, author, assayer, geologist and embezzler, was commissioned by the fifth Duke of Argyll, the Earl of Breadalbane and other landowners to conduct a mineralogical survey of the Highlands. He received the sum of £25 from the Highland Society to assist him in "so laudable an undertaking" (Carswell, 1950). Specimens of the Balephetrish Marble from Tiree were collected by Raspe during this survey and in 1791 a company, the Argyle Marble Company, was incorporated to work the marble. The Duke of Argyll and his son, the Marquis of Lorne, were leading officials in this company. Quarrying operations began under Raspe's supervision in the summer of that year, but, as reported by the Reverend N. Maclean in '<u>The New Statistical Account of Scotland</u>', "the difficulties of transportation and the attendant expenses were found to be so great, that, at the end of three years, the work was relinquished as an unprofitable, if not a losing speculation".

In his account of '<u>The Mineralogy of the Scottish Isles</u>' published in 1800, Jameson gave a brief account of the geology of Tiree and included descriptions of two specimens of marble from Balephetrish and a specimen of a mineral from Raspe's collection, believed to be corundum. The locality from which the corundum was collected is not given by Jameson and none has been observed during the present examination of the Tiree rocks.

Macculloch (1819) described some of the rocks and minerals of Tiree, paying particular attention to the mode of occurrence and the mineralogy of the marbles of Balephetrish. He mentioned the marbles again in a later work (1824) and on that occasion remarked that misuse of gunpowder during the operations, which had been carried out under Raspe's supervision, had almost ruined the marble quarry.

In Heddle's account of the mineralogy of Scotland (1901) there are several references to minerals found within the Balephetrish marbles and associated rocks. These rocks were also the subject of short papers by Coomaraswamy (1903) and Hallimond (1947) the contents of which will be referred to when the rocks are being discussed later in this thesis.

A geological map of the island has been published by the Geological Survey but no descriptive memoir has appeared, although a brief description of the geology was given in the '<u>Summary of Progress for 1922</u>'.

A geophysical survey to determine the extent of the magnetite-rich rock which outcrops at Loch a Phuil and to ascertain whether or not bands of similar rock exist beneath the drift elsewhere on Tiree was carried out by Whetton and Myer (1949). It was deduced that the Loch a Phuil magnetite-rich band is continous from the south coast at Balephuil Bay to Loch Bhasapoll, near the north coast, where it terminates against a flinty crush band. Prospecting in other parts of the island failed to reveal the presence of any other bands of strongly magnetic rock.

Present Investigations.

In the present investigation the Lewisian rocks of Tiree have been examined in the field and in the laboratory and an attempt made to reconstruct their metamorphic history. The metamorphic facies concept of Eskola, as modified by Turner (1948) and Fyfe, Turner and Verhoogen (1958), has been employed to classify the mineral assemblages within these rocks.

Laboratory work has involved the examination of some 250 thin-sections. Refractive indices, correct to 0.002, have been determined by immersion techniques and optic angles measured using a four axes universal-stage. The values for the optic angles quoted are corrected for the differences between the refractive indices of the minerals and those of the hemispheres of the stage. Composition of plagioclase has been estimated by comparing the values obtained for the refractive indices with the curves given by Kerr (1959).

Modal analyses have, in all cases, been calculated from sections cut at right-angles to any foliation or banding within the rocks; approximately 1,000 points were counted in each case. When these analyses are quoted in the text the values are given in volume per cent.

Chemical determinations were executed using the methods of Riley (1958). Rock-powders were dried at 110° before being analyzed; therefore no values for H_2O- were determined. The figure for 'CO_2 etc.' quoted in the analyses represents the total loss on ignition corrected for the H_2O+ content of the rock, and for the increase in weight due to the oxidation of the FeO during the ignition.

The specific gravities of rocks were determined on the Walker Steelyard; those of garnet and scapolite grains by use of heavy liquids and the Westphal Balance.

The references listed at the end of the thesis are abbreviated according to the system used in the _World List of Scientific Periodicals_.

General Geology and Nomenclature.

Lewisian Gneiss, often covered by a mantle of raised beach deposits or sand dunes and occasionally intruded by Tertiary dykes, makes up the bed-rock of the entire island. The foliation of the gneiss generally has a northerly trend although local deviations from that direction are common; its dip is always steep and often vertical.

The most commonly occurring rock type is a light to medium grey, banded, migmatitic, hornblende or hornblende-biotite gneiss in which are found many lenses, bands and blocks of basic, and less often of ultrabasic, rock. The amount of basic and ultrabasic material included is very variable but it is never entirely absent. This dominant variety of the gneiss is referred to in this thesis as the Banded Hornblende-Biotite-Migmatite or simply the Banded Migmatite.

Locally, on the southern slopes of Ben Hynish, the dominant mafic constituents of the gneiss are clinopyroxene and orthopyroxene instead of hornblende and biotite. The rock there is massive in character and banding is weak or absent. This phase of the gneiss, which has been found to have textural and mineralogical affinities with the acid and intermediate members of the charnockite series, is referred to as the Massive Migmatite.

At various places the Banded Migmatite grades into bands of pink Leucogranitic Gneiss, but only at the east end of the island, between Rudha Dubh and Port Ban, is this rock type developed in large amounts. There the Leucogranitic Gneiss is banded in various shades of pink and contains some bands of metasedimentary rocks but is generally free from basic and ultrabasic inclusions.

At two localities, Creagan Mora on the north coast and Hynish on the south, there occur masses, a few hundred yards wide, of biotite and biotite-garnet migmatitic gneiss which has apparently behaved in a much more plastic fashion during deformation than did the Banded Migmatite enclosing it. This phase of the gneiss is referred to as the Contorted Migmatite.

Within the mass of migmatitic gneiss there occur some bodies of non-banded or weakly banded intermediate, basic and ultrabasic gneiss, the outlines of which show a general concordancy with the trend of the enclosing migmatitic gneisses. The largest of these bodies is composed of intermediate charnockitic gneiss and makes up the northernly trending ridge of Ben Hough (388') in the north-west corner of the island. The small hill at Balephetrish is made up of dark greenish-grey, basic charnockitic gneiss; while another body of basic gneiss, in this case lacking charnockitic characteristics, occurs at Balephuil where it forms a fairly homogeneous mass about a mile long and one third of a mile broad elongated parallel to the trend of the enclosing migmatitic gneiss. A body of similar, non-charnockitic basic gneiss occur at Salum. The largest mass of ultrabasic gneiss occurs along the east side of the Ceann a Mhara peninsula where it forms a belt some five hundred feet wide and has sharp but concordant contacts with the adjacent Banded Migmatite. On the west coast of Eilean Ghreasamuill and Rhudha Hanais there occur smaller bodies of similar ultrabasic rock.

Bands and lenses of metasedimentary rocks, mostly marbles, calc-silicates, granulites and quartzites, are found within the gneissose mass at many localities throughout the island. These lenses and bands are generally elongated parallel to the trend of the enclosing gneiss and any compositional banding within them is most often parallel to that trend also. The largest mass of metasediments exposed, at Dun Gott, is some two hundred feet wide and half a mile long.

Bands and veins of acid pegmatite both parallel to and oblique to the banding of the gneisses are common throughout the island but quartz veins are of only very rare occurrence.

A band some 20' to 40' wide of flinty crush rock crosses the north-west corner of Tiree from Kilkenneth to The Green, and occasional patches of similar material containing brecciated fragments of gneiss occur at scattered localities throughout the island. Formation of flinty crush indicates that faulting took place while the rocks were in a brittle condition and probably buried at considerable depth.

Minor dislocations trending approximately east-west and occasionally truncating Tertiary dykes are frequently observed. They have a lateral displacement of only about ten or twenty feet. When they pass through an outcrop of Banded Migmatite a distinct reddening of that rock can be observed for some twenty or thirty feet on either side of them; microscopic examination reveals that this colouration is due to the presence of a network of fine, hematite-lined, cracks.

PART II

MIGMATITES

PLATE 2.

A. Banded Migmatite on the foreshore at Rudha Leacach.

B. Banded Migmatite at Caoles. Streaks and bands of acid pegmatite are common on this outcrop.

PLATE 2.

A.

B.

PLATE 3.

A. Basic lenses in the Banded Migmatite on the foreshore at Baugh.

B. Agmatite zone within the Banded Migmatite. Dun Balephetrish.

PLATE 3.

A.

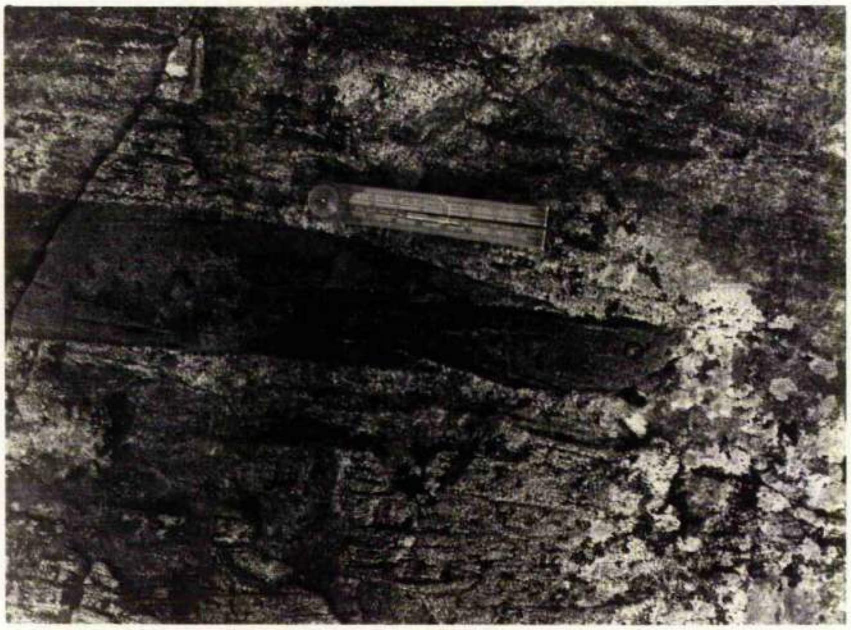
B.

PLATE 4.

A. Isoclinal fold within a basic lens included in Banded Migmatite at Dun Balephetrish.

B. Basic lens penetrated and dissected by acid material. Heanish foreshore.

PLATE 4.



A.

B.

PLATE 5.

A. Margin of irregular basic body included within the Banded Migmatite at Traigh nan Gilean. The contact between the basic rock and the Banded Migmatite can be seen running in a curved line from a few inches above the hammer head to the centre of the foreground. In the lower left hand corner of the picture a pegmatite band is seen to cut through the basic rock and continue into the adjacent migmatite.

B. Margin of the broad basic band at Port na Meidhaig at a point where it transgresses the banding of the enclosing migmatite for a few inches.

PLATE 5.

A.

B.

PLATE 6.

A. Crenulation in the Banded Migmatite at Caoles.

B. Block detached from the large ultrabasic lens at the Ringing Stone. The mineralogy and chemistry of this block are featured in figures 6 and 7. A portion of the large lens can be seen at the bottom of the picture.

PLATE 6.

A.

B.

BANDED MIGMATITE AND ASSOCIATED ROCKS.

1) Field Observations.

The Banded Migmatite is by far the most important rock type in Tiree for, as will be seen on the map, it constitutes over nine tenths of the total rock exposed on the island. It is a light to medium grey, generally medium-grained rock which almost always shows banding, the degree of development of which varies greatly from weak to well marked. Steeply plunging lineation due to the elongation of hornblende and other tabular minerals can occasionally be observed but is never a prominent feature and most often obscure or absent.

At almost all exposures the migmatitic nature of the rock is revealed by the abundant occurrence of basic and less often of ultrabasic inclusions, representing the palaeosome of the migmatite. Enclaves of metasediments, to be described later, occur at scattered locations within the Banded Migmatite mass. Bands of acid pegmatite are common, both parallel and transverse to the banding, and there are very occasional parallel quartz bands.

The banding, which is due to the partial segregation of the mafic and quartzo-felspathic components of the rock into separate layers, is, as stated above, very variable in degree of definition. Individual bands are often less than an inch in width and seldom more than two or three inches, but the acid layers, which are generally somewhat coarser grained than the mafic ones, sometimes become much broader and pass into pegmatite bands which may be several feet wide. Much lensing in and out occurs but in most outcrops many of the bands are continuous across the exposed surface. Bands which appear sharp and distinct on weathered surfaces are generally found, when the rock is broken open, to have gradational contacts and only very occasionally do the bands have truly sharp boundaries. The overall proportions of quartzo-felspathic and mafic material present are very variable and all gradations occur from dark mafic examples, which could be classified as plagioclase amphibolite, to quartzo-felspathic types representing transition to Leucogranitic Gneiss. Plate 2 illustrates the field appearance of the Banded Migmatite.

Almost always the dip of the banding is nearly vertical and it has most often an approximately north-south trend although, as will be observed on the map, there is some large scale folding in the area to the east of Balephetrish. Very occasional exposures show small scale folding or crenulation similar in style to that observed by Kranck in the migmatitic gneisses of Baffin Island (Kranck, 1954). Kranck believes that this sort of deformation originates during a period of increased plasticity after the main period of deformation. Plate 6-A shows an exposure exhibiting this crenulation.

The shape, size and abundance of the basic inclusions in the Banded Migmatite are variable, as is their relationship to the enclosing rock. They are made up of medium to dark grey, fine to medium grained material and most often occur as lenses from a few inches to many feet in length elongated parallel to the banding of the migmatite. The more slender of these are similar in nature to the mafic bands of the migmatite and, in fact a continuum exists between the two phenomena. However, the basic lenses generally have fairly distinct margins whereas the mafic bands, although they occasionally have sharp boundaries, more often grade into the adjacent acid bands.

Rather weakly developed foliation parallel to the banding of the migmatite is often observable in these lenses and this foliation is sometimes seen to be very faint in their central portions and to become more strongly defined towards the margins; a darkening of the basic rock close to the margins, due to an increase in the proportion of hornblende, is also sometimes observed. On the shore east of Balephetrish, where the Banded Migmatite is particularly well exposed, isoclinal folds, which are truncated against the enclosing acid material, are sometimes observed within the basic lenses, suggesting that folding had affected these basic rocks prior to the migmatitization process. The axial planes of these folds are generally parallel to the banding of the enclosing rock. An example of one of these folds is illustrated in Plate 4-A.

Partial or complete mantling of the basic inclusions by unfoliated, pegmatitic acid material, which grades into the Banded Migmatite over a few inches but has sharp contacts against the enclosed basic rock, is a commonly observed phenomenon. Sometimes this acid material is confined to one side of basic inclusions but more often completely mantles them, and ramifies through fissures breaking them up into groups of smaller blocks which may retain their parallel orientation but are in many cases to some extent disorientated with respect to each other. Plate 4-B illustrates a basic inclusion being penetrated and broken up by acid material.

Although lens-shaped bodies, the elongation and foliation of which are parallel to the banding of the enclosing rock, are the most common form of basic inclusion, there are many exposures of the Banded Migmatite in which the included basic material forms irregularly shaped blocks with a foliation disorientated with respect to the banding of the surrounding rock. Along the shore east of Balephetrish, as is illustrated in Plate 3-B, true agmatitic texture is occasionally developed. These disorientated blocks are most often irregular in outline, but a few fairly well rounded examples were observed on the foreshore near the disused quarry at Baugh. The rounded blocks are from 4 to 8 feet in diameter and possess faint foliation quite oblique to the banding of the enclosing rock, which in some cases bulges out around them; they are often partially and sometimes completely mantled by pegmatitic material.

At occasional locations, for example the south end of Traigh nan Gilean and the east end of Traigh Chornaig, there occur very irregularly outlined bodies of unfoliated, fine-grained basic rock, each some tens of feet in width. These bodies have blatantly discordant relationships with the banding of the migmatite but occasional basic bands two or three feet in width, which are concordant to the banding, lead out of them. No pegmatitic rimming of these basic bodies was observed but they are occasionally cut by pegmatite veins of various widths which continue, without interruption or change of direction, through the adjacent migmatite. Noticeable darkening of the basic rock on either side of these pegmatite veins is commonly observed and is due to a sharp increase in the amount of hornblende present in a zone a few centimetres wide on either side of the veins. Plate 5-A illustrates the discordant nature of the basic body at Traigh nan Gilean.

There also occur many bands up to about 40 feet in width of fine-grained basic rock similar in appearance and mineralogy to that which makes up the irregular bodies described above. These broad bands are generally concordant with the banding of the enclosing migmatite but occasionally their margins transgress the banding for a few inches (Plate 5-B). Faint foliation parallel to their margins is generally observed within these bands, a feature lacking in the irregular basic bodies.

Ultrabasic inclusions in the Banded Migmatite are volumetrically of much less importance than the basic ones just described. They are dark greenish-grey rocks, often somewhat coarser grained than the basic examples, and most often unfoliated or weakly foliated. They often form broad lenses or sub-rounded blocks several feet in width, but also occur as smaller streaks and lenses concordant with the banding of the enclosing rock. The banding of the gneiss curves out around the larger ultrabasic blocks and lenses and they are occasionally partly or wholly mantled by unfoliated pegmatitic material which grades within a few inches into the enclosing Banded Migmatite and ramifies through fissures and joints in the ultrabasic rock. In some cases plastic flow of this pegmatitic material around the margins of the ultrabasic inclusions has apparently detached fragments from them which are now seen to 'float' in the pegmatitic material a few inches from the ultrabasic body. Plate 6-B illustrates this phenomenon at the margin of a large ultrabasic lens on the north coast of Tiree near the Ringing Stone.

Quartzo-felspathic pegmatite bands are common throughout the Banded Migmatite. They vary in width from a few inches to twenty or thirty feet and their grain size varies from medium to coarse. The pegmatites are sometimes elongated parallel to the banding of the enclosing rocks, in which case they occasionally display weak foliation trending in the same direction, but are often sub-parallel or oblique to it. Cross-cutting pegmatite bands several feet in width often give off narrower concordant bands which, by reduction in width and grain size, grade into the acid portion of the migmatite. Blocks of basic and ultrabasic rock are found in the broader pegmatite bands. Weak foliation is often observed within these blocks and generally appears to be randomly orientated but occasional groups of included blocks have their foliation parallel to the general trend of the banding of the surrounding migmatite.

2) Texture, Mineralogy and Metamorphic Facies.

i) Banded Migmatite

ii) Basic Inclusions and Bands

iii) Ultrabasic Inclusions

iv) Soda-rich Zone at Creagan Mora

v) Pegmatite

i) Banded Migmatite.

The texture of this rock is seen, in section, to be generally xenoblastic granular with some tendency for the tabular minerals to be elongated parallel to the banding and for similar elongation of the large lobate quartz grains in the leucocratic bands. The grain size of the principal constituent minerals generally lies in the 0.5 to 2.0 mm. range but the leucocratic bands are often somewhat coarser and lobate quartz grains up to 8.0 or 10.0 in length occur.

Hornblende is almost always the dominant mafic mineral. It is generally accompanied by subordinate amounts of biotite and in occasional bands this mineral dominates over the hornblende. Diopsidic pyroxene occurs occasionally along with the hornblende and biotite and very occasionally there are a few grains of much altered hypersthene. These dark minerals are for the most part confined to the mafic bands but occasional grains, with identical optical properties to those in adjacent mafic bands, occur in the leucocratic bands. The leucocratic minerals are plagioclase, potash felspar and quartz. In the mafic bands plagioclase dominates almost to the exclusion of the other two but in the leucocratic bands the quartz and potash felspar, the proportions of which vary considerably, may together dominate over the plagioclase. Apatite, iron ore minerals, and occasionally zircon are present in accessory amounts, and chlorite and serpentine, secondary after mafic minerals, are of fairly widespread occurrence. Because of the irregular intergrading of mafic and leucocratic bands, individual modal analyses are of little value; but the accompanying table of modal analyses

Locations of the specimens featured in Table 1.

A-38-b	:	On the small peninsula of Rudha Leacach, one mile south of Caoles.
J-23-a	:	At Dun Balephetrish.
J-28-a	:	Foreshore at Rudha Saltaig, 600 yds. E.N.E. of Dun Balephetrish.
J-32	:	Foreshore at Loch Aulaig, 850 yds. E.N.E. of Dun Balephetrish.
J-139-b	:	North end of the disused quarry, south of the highway at Baugh.
J-137-b	:	On the foreshore south of the doctor's house at Baugh.
T-43-a	:	Outcrop on the beach 100 yds. N.E. of Eilean Ghreasamuill.
T-43-b	:	Adjacent to T-43-a.
T-66-c	:	Foreshore, 600 yds. north of Traig nan Gilean.
T-77-a	:	Outcrop at the southern end of Traigh nan Gilean.
T-134-a	:	Port na Meidhaig; two feet from the west margin of the basic band featured in Figure 3.
T-149-b	:	At Rudha Boraige Moire.
T-159-c	:	Foreshore, 900 yds. west of The Green.
16	:	Foreshore at the south-western corner of Vaul Bay.
17	:	Road-cutting 200 yds. east of Ruaig schoolhouse.

	*A-38-b	J-23-a	*J-28-a	*J-32	J-139-b	J-137-b	T-43-a	T-43-b	T-66-c	T-77-a	T-134-a	T-149-b	T-159-c	16	*17	Range
Hornblende	1.3	22.7	6.9	9.3	29.0	0.6	40.5	0.4	0.6	20.5	10.5	1.5	6.6	8.8	27.5	0.4 - 40.5
Clino-pyroxene	-	-	-	0.1	-	-	1.9	-	1.7	2.2	-	-	-	-	-	0.0 - 2.2
Ortho-pyroxene	-	-	-	-	-	-	5.3	-	-	-	-	-	-	-	-	0.0 - 5.3
Biotite	14.6	-	5.6	1.1	-	-	0.5	4.7	-	7.2	5.0	0.1	11.5	5.1	4.6	0.0 - 14.6
Plagioclase	41.4	54.8	45.3	42.1	40.0	53.4	39.2	57.4	58.9	60.6	47.8	48.6	66.5	46.5	45.5	39.2 - 66.5
K-Felspar	14.2	1.9	20.9	25.7	0.7	23.7	5.0	10.0	8.6	0.3	14.4	10.2	2.2	20.3	6.9	0.3 - 23.7
Quartz	28.1	14.1	21.2	21.5	24.4	15.0	7.1	18.0	24.5	-	12.8	35.1	3.8	18.2	14.7	0.0 - 35.1
Ore	0.1	-	-	0.1	-	0.2	0.5	0.4	1.3	6.3	2.2	0.4	3.1	0.9	0.8	0.0 - 6.3
Apatite	0.4	0.5	-	0.1	-	0.2	-	0.2	-	0.9	0.5	0.1	-	0.1	-	0.0 - 0.9
Serpentine & Chlorite	-	6.0	-	-	6.0	6.8	-	9.0	4.4	2.2	6.9	4.0	6.2	-	-	0.0 - 6.9
Zircon	tr.	-	-	-	-	-	-	-	-	-	-	-	0.1	tr.	-	0.0 - 0.1

(*Specimen also analyzed chemically.)

Table 1: Modal analyses of examples of the Banded Migmatite.

	J-28-a	J-32	A-38-b	17
SiO_2	60.02	68.98	65.50	62.37
Al_2O_3	16.80	14.82	16.08	16.27
Fe_2O_3	3.01	1.27	0.98	2.22
FeO	3.70	1.67	3.77	3.38
MnO	0.09	0.02	0.04	0.08
MgO	2.25	1.21	2.56	2.18
CaO	5.79	3.71	3.61	5.88
Na_2O	4.62	4.81	3.82	4.40
K_2O	2.32	2.51	3.35	2.30
TiO_2	0.46	0.30	0.37	0.45
P_2O_5	0.09	0.13	0.10	0.11
H_2O+	0.63	0.60	0.48	0.37
CO_2 etc.	0.31	-	0.20	0.25
	100.09	100.03	100.86	100.26

Table 2: Chemical composition of four of the specimens of Banded Migmatite featured in Table 1. (Analyst: I.G.L. Sinclair)

of a range of sections cut at right angles to the banding gives a general picture of the mineralogy and the sort of variation encountered within this division of the Tiree Lewisian (Table 1). Table 2 shows the chemical composition of four of the specimens featured in Table 1.

Features of the individual constituent minerals are described below:

<u>Hornblende</u>: The hornblende is a variety strongly pleochroic with X - straw coloured, Y - light brownish green and Z - medium, slightly brownish, green. The grains, which generally show some tendency to elongation in the direction of the banding, occur as separate individuals and in straggling bands and irregular clusters. When in mutual contact in the bands and clusters the grains have often straight, sub-idioblastic margins but when they abut against the leucocratic minerals their margins are often embayed and sometimes are frayed and have narrow reaction rims. Sometimes small flecks of hornblende are included in felspar grains and occasionally several of these, within a single felspar grain, are in optical continuity. Narrow bands of opaque ore often occur along the junction between adjacent hornblende grains and narrow bands of similar material often traverse hornblende grains in a direction approximately normal to the direction of the banding. These narrow ore bands are sometimes continuous across adjoining hornblende grains. Similar bands occur spasmodically within the plagioclase grains, and are very occasionally continuous with those in the hornblende, but they are most often absent in the biotite grains. Patches of irregular dark brown staining are occasionally visible in the hornblende which, although often free from inclusions, sometimes contain small, rounded blebs of apatite,

felspar and quartz. In the case of the last two minerals, however, these may be protruberances of adjacent lobate grains, rather than true inclusions. The hornblende is often intergrown with, and sometimes appears to be being replaced by, biotite; elsewhere it is partially, and sometimes almost completely, replaced by pale green, slightly pleochroic, chlorite which often contains many specks and granules of ore. The optic angle, $-2V$, of the hornblende varies from 60 to 71 degrees, N_{α} from 1.664 to 1.667, N_{γ} from 1.686 to 1.688 and $Z \wedge c$ from 16 to 20 degrees. Because of the many different chemical variations possible in hornblende it is not possible to correlate these properties with the chemistry of the mineral. About Winchell's (1951) complex diagrams for the correlation of the optics and chemistry of hornblende, Engel (1959) has said that they "..... suggest precise, sympathetic relations between optics and composition that cannot be demonstrated."

Biotite: The biotite forms slender laths, or clusters of laths, which often have a rather ragged outline. In most cases they show some tendency to elongation parallel to the banding of the rock, although this tendency is only occasionally well-marked. The biotite is strongly pleochroic with X - yellow, Y - medium reddish brown, Z - medium or dark reddish brown. In many cases the biotite is intergrown with the hornblende and very occasionally small flecks of biotite are seen to be developing around the margins of hornblende grains. All degrees of alteration of biotite to chlorite, from slight to complete, can be observed. The only inclusions within the biotite laths are small specks and rods of ore minerals.

Pyroxene: Minor amounts of clinopyroxene occur occasionally and a few specimens contain some, mostly altered, hypersthene.

The clinopyroxene is a pale green, non-pleochroic variety which forms generally equant, xenoblastic, grains. These are often intergrown with hornblende and locally contain small inclusions of the latter mineral. The clinopyroxene grains are sometimes rimmed and traversed by narrow ore bands, as are the hornblendes, and they are frequently partly and at times almost completely replaced by very pale green chlorite. The chlorite may have minor amounts of calcite intergrown with it.

On the rare occasions on which hypersthene has been observed, it is seen to be almost completely replaced by antigorite. Only a few fresh patches, showing pleochroism in shades of pale pink, remain within grains of the secondary material.

Plagioclase: Plagioclase is the dominant and sometimes the only leucocratic mineral in the dark bands of the gneiss. It also occurs in important amounts, and is occasionally dominant over quartz and potash felspar, in the leucocratic bands. It forms xenoblastic grains, the larger of which are elongated parallel to the banding of the rock, which are sometimes fresh but often partially or completely sericitized. Twinning on both the albite and pericline laws is usually seen but it generally is rather weakly defined with very fine lamellae. Slight normal zoning is sometimes observed within the plagioclase grains. Anti-perthitic inclusions of potash felspar, forming groups of minute elongate lenses or sub-rectangular bodies in optical continuity, are seen in many of the plagioclase grains, and in portions of the grains which abut against potash felspar there is often the development of myrmekitic quartz intergrowths. A less common, but occasionally observed, feature at the junction of plagioclase and potash felspar grains is the development of a narrow clear rim around an otherwise sericitized plagioclase grain. Groups of tiny, dark brown or black rods, probably of rutile, occur within the plagioclase grains. These may be randomly orientated but most often they are arranged in parallel groups and occasionally, within one plagioclase grain, two, and sometimes even three, different directions of orientation of groups of these tiny rods can be observed. In a few examples the plagioclase grains are crossed by narrow bands of ore which sometimes have clinging to them some chlorite and which, as with similar bands within the hornblendes, usually trend in a direction approximately normal to the banding of the rock. The plagioclase is most often an oligoclase in the range An_{20} - An_{30}, but occasional examples as sodic as An_{15} occur.

<u>Potash Felspar:</u> As will be seen from the table of modal analyses, the potash felspar is very irregular in occurrence and sometimes may be present only as anti-perthitic inclusions in plagioclase. It is generally fresh and forms completely xenoblastic grains which may embay into the plagioclase and contain inclusions of it. This sort of texture was observed by Bellière (1960) in the migmatitic gneisses of the Aiguilles Rouges and is considered by that worker to be indicative of replacement of plagioclase by potash felspar. Cross-hatched twinning is sometimes quite well developed but in many cases it is confined to the marginal zones of grains, the centres of

which show no sign of the presence of twinning. It may be that, as suggested by Wahlstrom and Kim (1959), the occurrence of grains with untwinned cores and twinned margins indicates that the cores are composed of a phase stable at the highest temperature attained during metamorphism while the margins are composed of microcline formed by a later partial inversion of the high temperature phase. The fact the optic angle, -2V, ranges from 50 to 85 degrees, and may show a range of as much as 10 degrees within a single thin-section, tends to support this theory of partial inversion. Perthitic groups of little ovoid plagioclase blebs, often partially sericitized, are sometimes included in the potash felspar and optical continuity exists between all of these within one host grain. Many of the potash felspar grains also include groups of slender tapering quartz ribbons which usually commence at the margin of the grain and taper off towards its centre.

Quartz: Quartz, always showing undulose extinction, occurs in the mafic bands as irregular, xenoblastic grains of the same order of size as those of the other principal constituent minerals, but in the leucocratic bands it often forms lobate grains elongated parallel to the banding of the gneiss which are several times larger than the accompanying felspar grains. The quartz is often free from inclusions although it occasionally contains little fragments of biotite, hornblende and felspar and very occasionally, tiny rounded grains of zircon. Trains of very minute bubbles are sometimes seen to cross the quartz grains, most often in direction approximately normal to that of the banding of the rock. Minor amounts of quartz also occur, as mentioned above, as myrmekitic intergrowths within plagioclase grains and there are very occasionally thin films of quartz along the contacts between felspar and biotite grains.

Accessories: Small, sub-rounded laths of apatite, which only occasionally attain a length of 0.5 mm., are found in most sections and there are occasional tiny rounded zircon grains. Ore minerals are often confined to small inclusions and bands in other minerals but very irregularly outlined, discrete grains are sometimes observed and are generally intergrown with the mafic minerals.

Metamorphic Facies:

The mineral assemblage described above in the Banded Migmatite is:- Oligoclase-potash felspar-quartz-hornblende-biotite, with minor amounts of ore, apatite, serpentine, chlorite and zircon. In addition to these minerals there occur very occasionally minor amounts of clinopyroxene and rarely some much altered hypersthene.

The plagioclase is sometimes anti-perthitic and the potash felspar sometimes perthitic, and when the two varieties are in contact the plagioclase contains myrmekitic quartz intergrowths and, if sericitized, has clear rims where it abuts against the potash variety. There is some evidence to suggest that the potash felspar crystallised as orthoclase, but is now partially inverted to microcline.

The mineral assemblage is one stable in the sillimanite-almandine subfacies of the almandine amphibolite facies (Fyfe, Turner and Verhoogen, 1958) while the occasional occurrence of clino and orthopyroxene suggests local transition to the hornblende-granulite subfacies of the granulite facies. The textural features of the felspars noted above are somewhat suggestive of crystallization under the conditions of temperature and pressure appropriate to the granulite rather than to the almandine-amphibolite facies (Turner and Verhoogen, 1951) and, as will be described below, granulite facies assemblages are found in the broad basic bands within the Banded Migmatite mass. It might be postulated, therefore, that the sillimanite-almandine subfacies assemblage now observed in the Banded Migmatite was formed by the diapthoresis of a pre-existent granulite facies assemblage; but no textural evidence, such as the existence of pyroxene relics within the hornblende grains, has been observed to validate this assumption. However, under the same conditions of high temperature and pressure, assemblages typical of either the topmost subfacies of the almandine-amphibolite facies or the lower subfacies of the granulite facies may be generated, depending on the water vapour pressure (Fyfe, Turner and Verhoogen, 1958). It is therefore possible that the assemblages in the Banded Migmatite and in the included broad basic bands formed contemporaneously, under approximately the same conditions of temperature and pressure, but that the presence of water in the former and relative lack of it in the latter caused the apparent difference in the metamorphic grade of the mineral assemblages formed.

In Figure 1 below, the four analyses of Banded Migmatite from Table 2 are plotted on an ACF diagram for the sillimanite-almandine subfacies of the almandine-amphibolite facies and in Table 3 the actual mineral assemblages found in the rocks are compared with the theoretical ones indicated by the

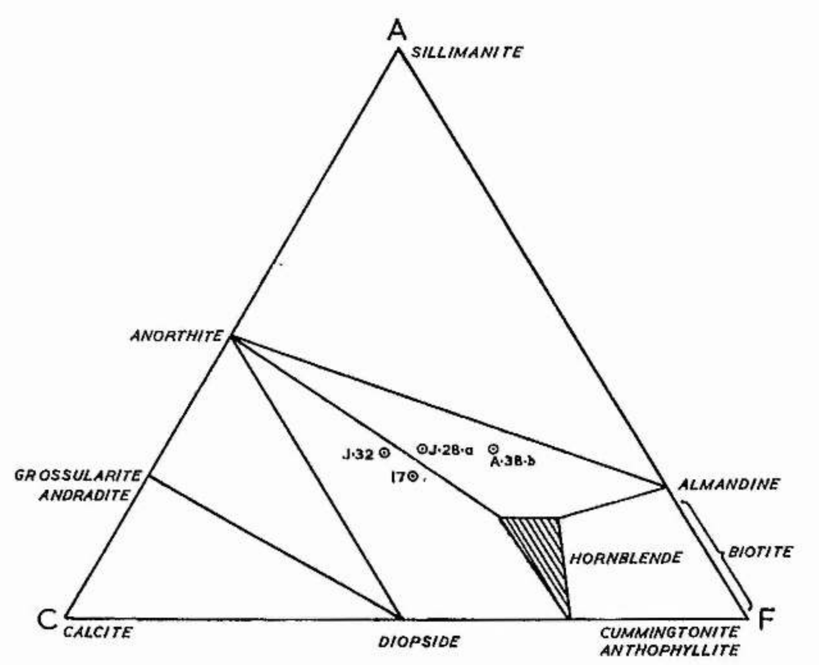


Figure 1: Plot of the analyzed specimens of Banded Migmatite on the ACF diagram for the sillimanite-almandine subfacies. (Diagram after Fyfe et al., 1958). N.B.: Potash felspar and quartz are possible additional phases in the specimens plotted on this diagram.

	Actual Assemblage	Theoretical Assemblage
J-32	Plagioclase, potash felspar, quartz, hornblende and minor diopside and biotite.	Plagioclase, potash felspar, quartz, hornblende and diopside.
17	Plagioclase, potash felspar, quartz, hornblende and biotite.	Same as J-32.
J-28-a	Plagioclase, potash felspar, quartz, hornblende and biotite.	Plagioclase, potash felspar, quartz, hornblende, almandine and perhaps biotite.
A-38-b	Plagioclase, potash felspar, quartz, biotite and minor hornblende.	Same as J-28-a.

Table 3: A comparison of the actual mineralogical assemblages found within those examples of the Banded Migmatite plotted on Figure 1 with the theoretical assemblages suggested by their positions on that figure.

diagram. The principal disparity between the theoretical and actual assemblages is the occurrence in the latter of biotite rather than the almandine suggested by the former. The occurrence of biotite rather than almandine in similar amphibolite facies rocks has been noted by Wahlstrom and Kim (1959) who consider it may be an expression of a low FeO/MgO ratio as suggested by Turner (1958), or it may indicate formation of biotite during diaphthoretic readjustment of the rocks after the main period of metamorphism. In this case, since biotite laths cut through hornblende grains and little flecks of biotite occur occasionally around the margins of these grains, it does seem possible that the biotite is, at least in part, of diaphthoretic origin. In specimen number 17 some diopside would be expected to occur according to its position on the ACF diagram, but in two thin-sections examined none was observed. Small amounts of diopside may possibly occur, however, outwith the area of these sections.

ii) Basic Inclusions and Bands.

The small lenses, the sub-rounded and sub-angular blocks, the broad bands and the irregularly outlined basic bodies included within the Banded Migmatite are all texturally and mineralogically similar except that hypersthene and garnet, which are fairly common constituents of the larger blocks and bands, are generally absent in the smaller blocks and lenses.

Table 4, overleaf, is made up of modal analyses of examples of the basic lenses and blocks from scattered localities within the Banded Migmatite and illustrates the range of mineralogical composition encountered.

Locations of the specimens featured in Table 4.

A-38-a : On the small peninsula of Rudha Leacach, one mile south of Caoles.
J-23-b : At Dun Balephetrish.
J-41-a : Foreshore 350 yds. west of the Ringing Stone.
J-91-e : Small peninsula of Ard Beag, 440 yds. east of Clachan Mor.
J-137-a: On the foreshore south of the doctor's house at Baugh.
J-139-a: North end of the disused quarry, south of the highway at Baugh.
P-6-b : Foreshore 100 yds. east of the Ringing Stone.
T-7-a : Dun Mor Vaul on the west side of Vaul Bay.
T-42-b : Outcrop on the beach 50 yds. east of Eilean Ghreasamuill.

	A-38-a	J-23-b	J-41-a	J-91-e	J-137-a	J-139-a	P-6-b
Hornblende	62.4	28.1	23.5	71.8	20.2	6.6	61.1
Clinopyroxene	0.2	18.5	33.2	2.8	20.0	23.7	1.7
Orthopyroxene	-	-	-	4.6	5.2	1.5	-
Plagioclase	23.0	46.6	40.5	17.1	46.6	41.7	37.2
K-Felspar	-	0.5	-	-	-	2.0	-
Quartz	11.0	2.2	-	-	-	7.8	-
Biotite	-	-	-	1.9	-	-	-
Garnet	-	-	-	-	2.4	7.9	-
Apatite	0.1	-	0.7	0.3	-	-	-
Ore Minerals	2.2	4.2	2.1	1.5	5.6	8.7	-
Sphene	0.5	-	-	-	-	-	-
Serpentine & Chlorite	0.6	-	-	-	-	-	-

Table 4: Modal analyses of basic inclusions within the Banded Migmatite.

One of the examples in this table, T-42-b, is of a lens which is seen in the field to be intimately penetrated by acid material; its mode reveals that it is mineralogically analogous to some of the specimens of Banded Migmatite. Variations in the mineralogy across two of the broad basic bands elongated parallel to the banding of the migmatite are shown graphically in Figures 3 and 5. The pattern of mineralogical change revealed in these diagrams is discussed when the metamorphic facies of the basic rocks is considered below.

These rocks generally have a xenoblastic texture, with most grains in the 0.25 to 1.5 mm. size range, and there is some tendency for the mafic minerals to be aggregated in irregular clusters some 2.0 to 3.0 mm. in diameter. However, in the smaller lenses and close to the margins of the larger bodies, where hornblende often predominates to the partial or complete exclusion of pyroxene, elongation of the hornblende grains parallel to the margins of the basic rock is fairly well-marked. Plates 7-A and 7-B contrast the texture of the interior of a basic band with that of its margin.

The mode of occurrence and features of the constituent minerals of these basic rocks are now described;

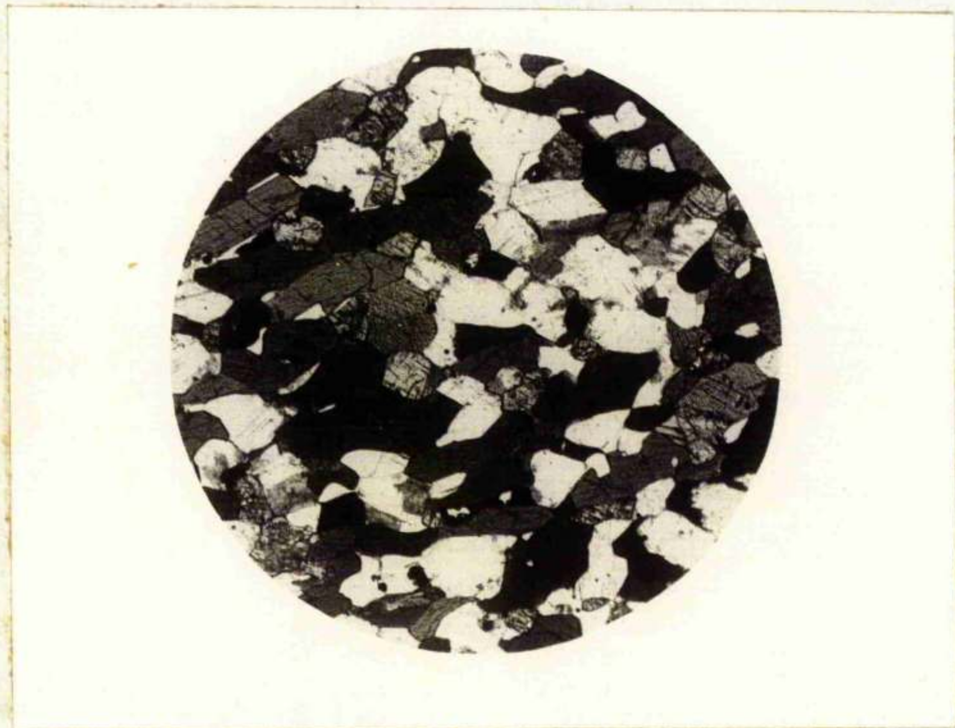
Hornblende: This is most often the dominant mafic mineral and is a variety strongly pleochroic from pale straw to deep, somewhat brownish, green with an occasional bluish tint close to the margins of grains. It is usually fresh, but is occasionally partly altered to light green chlorite and very rarely partly replaced by a colourless amphibole. When in contact with each other the hornblende grains often have straight, idioblastic margins, but they are generally embayed by and have narrow reaction rims against plagio-

PLATE 7.

A. Texture of the marginal zone of the Ballymartin Basic band. The principal dark mineral is hornblende, and clinopyroxene occurs in subsidiary amounts. (X 15)

B. Texture of the hornblende-poor intermediate zone within the same basic band. The hornblende and clinopyroxene are in this case accompanied by some orthopyroxene and minor amounts of garnet. (X 15)

PLATE 7.



A.

B.

clase and sometimes against pyroxene. Occasionally, as illustrated in Plate 8, hornblende appears to have been partially replaced by clinopyroxene, with concomitant release of granular ore; and within clinopyroxene grains optically continous groups of small hornblende inclusions occasionally occur. In one basic lens examined, hornblende occurs only as inclusions within clinopyroxene. Irregular granules of ore minerals often occur within the hornblende grains and narrow strips of ore line the interfaces between them. Patches of dark brown staining are often visible in the hornblende grains and rounded blebs of felspar and quartz, which are probably protruberances of lobate grains of those minerals, can be observed within them also. The The optic angle, $-2V$, of the hornblende ranges from 55° to 75°, $N\alpha$ from 1.663 to 1.679 and $N\gamma$ from 1.687 to 1.698.

<u>Clinopyroxene:</u> The clinopyroxene is generally very pale green and occasionally displays just perceptible pleochroism from pale green to pale pinkish green. It is usually fresh but occasionally slightly chloritized along cracks; and it forms xenoblastic to sub-idioblastic, generally equant, grains which embay into hornblende and are often themselves embayed by felspar and quartz. Small specks of ore and blebs of quartz occur within the clinopyroxene grains and they occasionally contain small groups of optically continuous hornblende inclusions.

Typical (110) cleavages and occasional (001) partings occur in many grains and occasionally two sets of cleavages or partings which look like typical amphibole cleavages can be seen. Groves (1935) and Parras (1958) have used the existence of amphibole-like cleavages in pyroxene grains as

PLATE 8.

Possible replacement of hornblende by clinopyroxene in the Ballymartin basic band. In the centre of the picture a small grain of dark hornblende is seen rimmed by granular ore and enclosed by clinopyroxene. (X 60) evidence of the derivation of the latter from the former mineral. Stereographic projection of the amphibole-like cleavages in the present case revealed that the angle between them is close to 50° and that they intersect on the c-axis, but that the optic axial plane does not bisect the acute angle between them, and in fact lies outwith that angle. In this case, therefore, it does not seem likely that these are relics of pre-existent amphibole cleavages. Since neither Groves nor Parras mention the crystallographic relationships of the relic amphibole cleavages they observed, their relevance as evidence of replacement of amphibole by pyroxene cannot be estimated.

The optic angle, +2V, of the clinopyroxene ranges from 56° to 60°, N_{α} from 1.679 to 1.684, N_{γ} 1.707 to 1.713 and the birefringence from 0.026 to 0.030. These properties correspond to those of the salite member of the diopside-hedenbergite series. (Hess, 1949)

<u>Orthopyroxene:</u> Orthopyroxene is rarely present in the smaller basic blocks and lenses but it is generally present in the larger ones and in the large irregular bodies and broad bands. It is pleochroic from pale green to pale pink and forms xenoblastic, generally equant, grains which often show some alteration to bastite, peripherally and along irregular cracks. Small inclusions of hornblende and ore are occasionally seen in the orthopyroxene. Oblique extinction of the orthopyroxene, which has often been noted in rocks of the charnockitic series (Groves, 1935; Picamuthu, 1953; Quensel, 1951; Parras, 1938), is a common feature in the present case. It has been suggested that this phenomenon may be due to the survival of amphibole cleavages in a grain converted from amphibole to orthopyroxene

during up-grading of the metamorphic facies, but Parras (1958) has pointed out that it is more likely to be due to a lack of grains cut parallel to the c-axis in any one section. The optic angle, -2V, ranges from 53° to 58° and may show a range of as much as four degrees within a single thin-section. Typical examples give N γ values of 1.714 and 1.716. These are properties of an iron-rich hypersthene. (Hess, 1952)

Biotite: Sometimes small flecks of biotite occur clinging to the margins of hornblende grains and apparently forming at the expense of that mineral. The biotite is strongly pleochroic with X - pale yellow, Y - brown, Z - medium to dark reddish brown, is generally fresh but occasionally partially chloritized and contains occasional streaks and grains of ore. It has an optic angle of zero or close to zero and N γ ranges from 1.645 to 1.650, suggesting a fairly iron-rich biotite (Winchell, 1951)

Garnet: Garnet occurs only in the larger of the basic blocks and in the broad bands and irregular bodies. It is pale pink and occurs as irregular, xenoblastic to sub-idioblastic grains which contain small inclusions of hornblende, clinopyroxene, ore, quartz and plagioclase and are often intergrown with pyroxene and less often with hornblende grains. The refractive index and specific gravity of the garnet, 1.785 and 3.95, respectively, indicate that it is an almandine-pyrope with a composition about almandine 70% and pyrope 30%.

Plagioclase: Plagioclase is always an abundant constituent, often making up more than forty percent of the volume of these rocks. It forms xenoblastic, more or less equant grains which are often slightly, and sometimes heavily, sericitized. Albite and sometimes pericline twinning is generally developed but often weakly defined, and slight normal zoning is occasionally observed. The plagioclase often embays into hornblende grains and contains small inclusions of that mineral, small groups of which, within a single plagioclase grain, are sometimes optically continuous. Less often it contains small irregular fragments of biotite and pyroxene and small grains of ore. In the lenses and blocks the plagioclase is generally oligoclase or andesine in the An_{20} to An_{45} compositional range, with occasional examples as sodic as An_{12}; but in the broad basic bands it is generally andesine-labradorite in the An_{40} to An_{50} range and may be as sodic as An_{30} within a few inches of the margins of these bands. In one of the broad basic bands, although most of the plagioclase is fresh, there occur irregular clusters of grains which are heavily sericitized and contain inclusions of epidote. These clusters appear in hand specimen as white, sometimes lath-shaped, flecks up to about 5.0 mm. in length. They may possibly indicate the loci of plagioclase phenocrysts in an original igneous rock.

Quartz: Interstitial lobate grains occasionally occur associated especially with garnet and ore. They show markedly strained extinction and are sometimes crossed by trains of minute bubbles. The association of the quartz with garnet suggests that it may have formed from silica released during the crystallization of the latter mineral.

Ore Minerals: Small, irregular grains of ore are common and there are occasional larger, skeletal grains up to 2.5 mm. in diameter which are sometimes intergrown with garnet and contain aggregates of granular quartz in their interstices. Small flecks of biotite sometimes occur around the margins of these larger ore grains.

Accessories: Small fresh laths of moderately birefringent scapolite occur in minor amounts in some of the broad basic bands. When scapolite does occur within a basic band it generally appears to be distributed uniformly throughout rather than concentrated close to the margins, a circumstance which, perhaps, suggests that sufficient CO_2, Cl, SO_3 and H_2O were present in the material of the basic rock to enable the small-scale genesis of scapolite, rather than that these constituents were introduced from an extraneous source.

Small sub-rounded laths of apatite, irregular grains of watery brown sphene and tiny sub-rounded zircon grains occur sporadically in very minor amounts.

Metamorphic Facies:

The principal constituent minerals of the basic lenses and blocks are plagioclase, hornblende, clinopyroxene and quartz with occasional biotite. This assemblage is that typically generated by the crystallization of basic rocks in the sillimanite-almandine subfacies of the almandine amphibolite facies, while the occasional occurrence of garnet and hypersthene suggests local transitions to granulite facies assemblages. (Fyfe et al., 1958)

Close to the margins of the broad basic bands and of the irregular basic bodies sillimanite-almandine subfacies assemblages, such as that just noted, are generally found; but in the interiors of these modifications the tenor of the hornblende is lower and varying amounts of clinopyroxene, orthopyroxene and garnet are found, this combination being indicative of crystallization under granulite facies conditions (Fyfe et al., 1958). In those bands which are up to about fifteen or twenty feet in width the concentration of granulite facies minerals attains a maximum near their centres. However, in the still broader masses the concentration of these high grade minerals is highest in zones about half-way between the centres and the margins, while at their centres the relative proportion of hornblende present is higher than in the intermediate zones although still much lower than at the margins.

A detailed mineralogical and chemical examination of several specimens from two of the broader basic bands was made. One of the bands examined is located on the foreshore near the village of Ballymartin and the other at Port na Moidhaig; The locations of the bands are illustrated in the accompanying sketch maps (Figures 2 and 4). Figures 3 and 5 illustrate the variations in the amounts of the constituent minerals present across the bands and Tables 5 and 6 show the chemical composition of four specimens from each of the bands; the analyzed specimens were collected along the same section-lines as the specimens featured in Figures 3 and 5.

It will be observed from the figures that in the Ballymartin band the amphibolite facies mineral, hornblende, is the dominant mafic component whereas in the Port Na Moidhaig example the typical granulite facies minerals, orthopyroxene, clinopyroxene and garnet, predominate. However, the same general pattern of mineralogical variation can be observed in both bands:

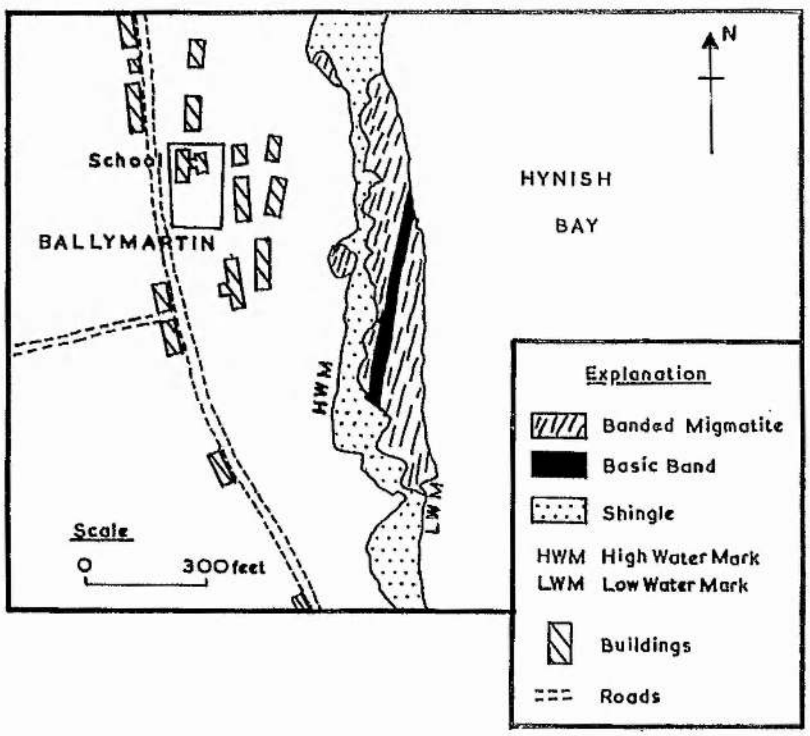


Figure 2: Sketch-map showing the location of the basic band on the foreshore at Ballymartin. The mineralogy of this band is featured in Figure 3.

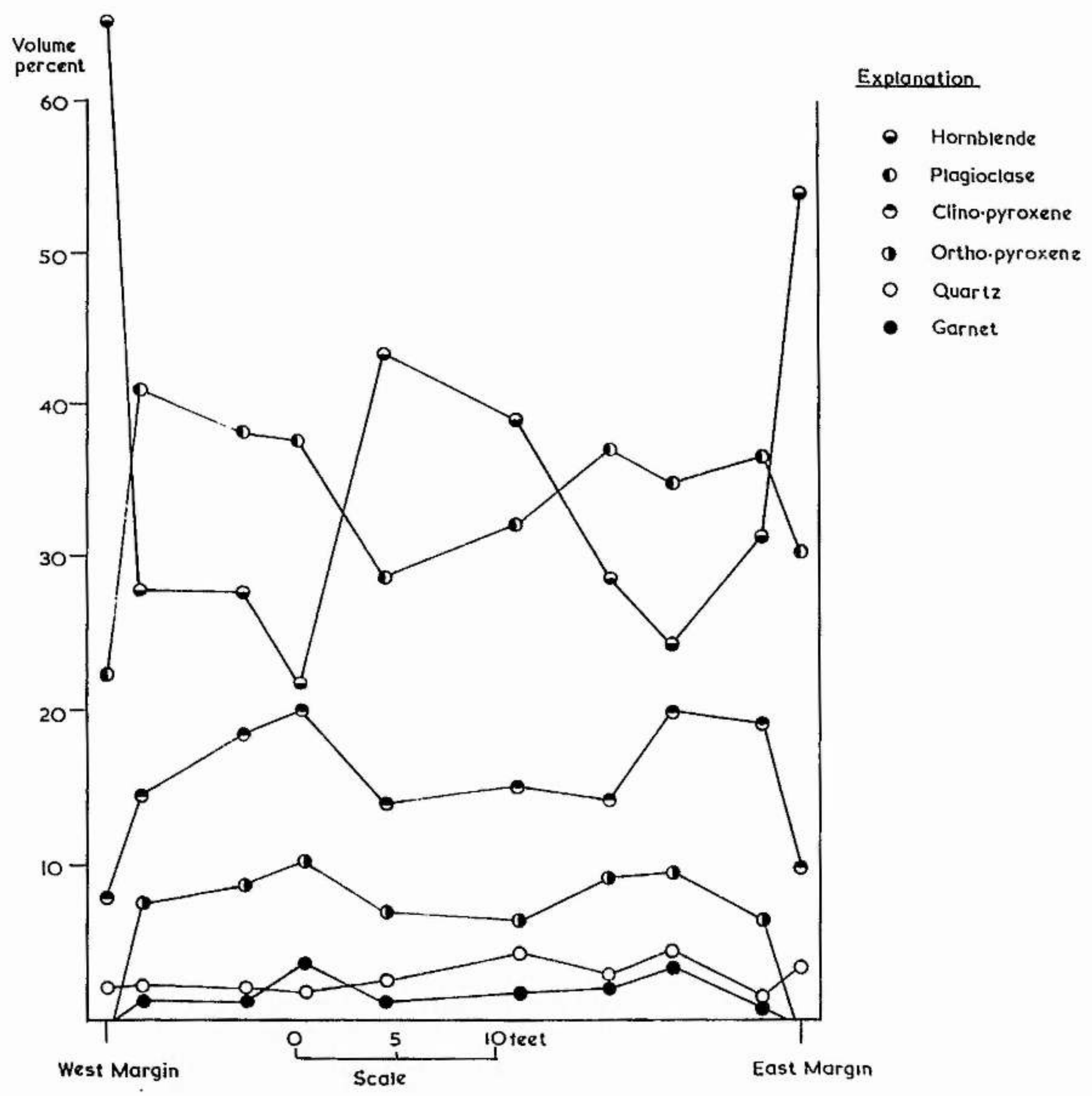


Figure 3: Diagram constructed from a series of modal analyses to illustrate the variations in the mineralogical composition of the basic band at Ballymartin.

	1	2	3	4
SiO_2	50.42	49.00	50.59	50.58
Al_2O_3	14.33	13.73	13.16	13.01
Fe_2O_3	4.38	4.48	3.90	3.49
FeO	9.71	10.16	10.09	10.02
MgO	7.40	7.97	7.02	7.91
CaO	8.57	10.80	11.09	10.96
Na_2O	2.65	2.85	2.00	2.30
K_2O	1.15	0.25	0.21	0.35
TiO_2	0.89	1.02	0.91	0.90
P_2O_5	0.02	0.01	0.02	0.01
MnO	0.07	0.25	0.22	0.21
H_2O+	0.66	0.47	0.35	0.70
Total	100.25	100.99	99.56	100.44
Specific Gravity	3.061	3.077	3.106	3.080

Analyst: I.G.L. Sinclair.

Table 5: Chemical analyses of the basic band at Ballymartin along the section line from which the specimens used to construct figure 3 were collected:

1. At east margin
2. 2'0" from east margin
3. 6'6" " " "
4. 14'2" " " "

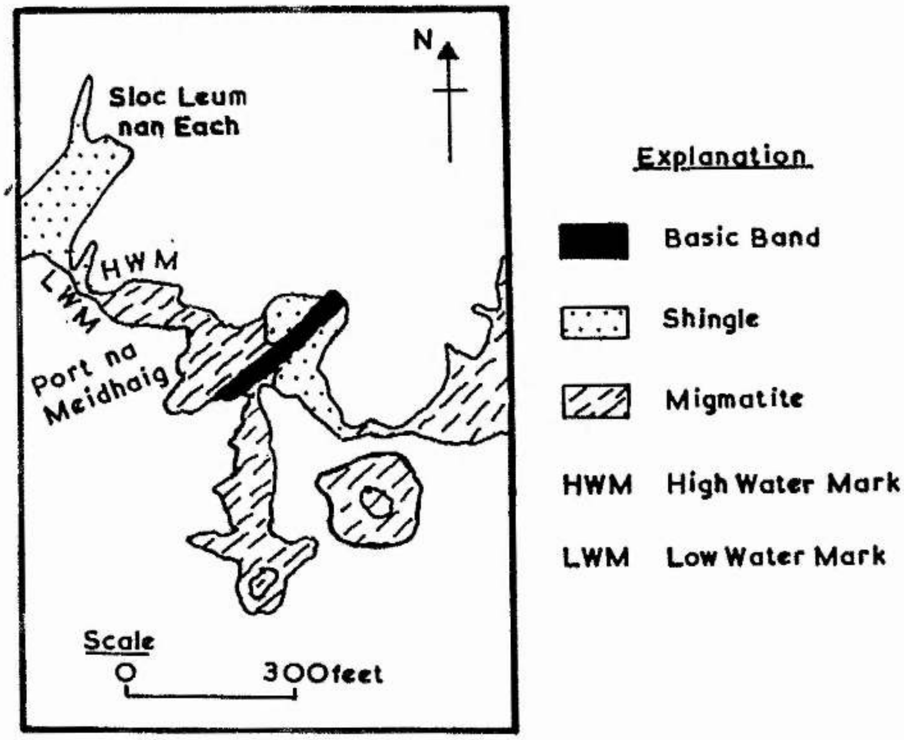


Figure 4: Sketch-map showing the location of the basic band at Port na Meidhaig, the mineralogy of which is illustrated in Figure 5. The migmatite enclosing this band is transitional between the Massive and the Banded types.

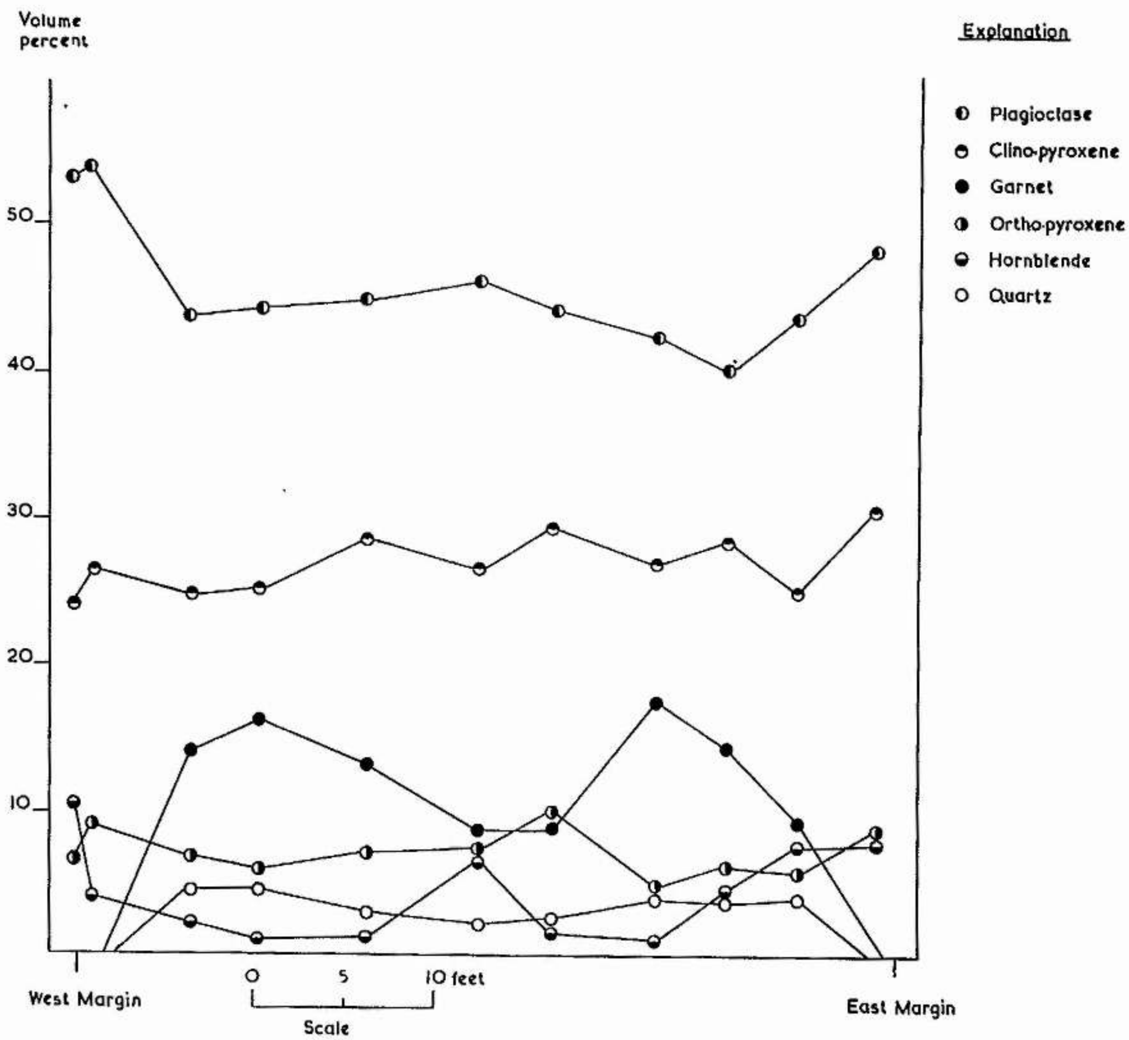


Figure 5: Diagram constructed from a series of modal analyses to illustrate the variations in the mineralogical composition of the basic band at Port na Meidhaig.

	1	2	3	4
SiO_2	49.15	49.35	48.16	49.27
Al_2O_3	14.21	14.35	13.78	13.98
Fe_2O_3	5.55	3.98	5.31	4.20
FeO	7.98	9.18	8.92	8.98
MgO	7.46	7.14	7.10	7.21
CaO	10.91	11.75	11.56	11.33
Na_2O	3.50	2.15	2.55	2.70
K_2O	0.35	0.38	0.35	0.40
TiO_2	0.88	0.93	0.84	0.86
P_2O_5	0.03	0.03	0.03	0.02
MnO	0.21	0.24	0.24	0.20
H_2O +	0.37	0.45	0.26	0.33
Total	100.60	99.93	99.10	99.48
Specific Gravity	3.029	3.116	3.154	3.093

Table 6: Chemical analyses of the basic band at Port na Meidhaig along the section line from which the specimens used to construct figure 5 were collected:

1. 6" from east margin
2. 5'6" " " "
3. 14'0" " " "
4. 24'0" " " "

the concentrations of granulite facies minerals are highest in zones intermediate between the margins and the centres of the bands while hornblende is most abundant at the margins and in the central zones.

The chemical analyses were made to determine whether or not the mineralogical changes observed within the bands are accompanied by any significant variations in their bulk compositions. The results reveal that chemical variations are, on the whole, slight, although there is an increase in alkalies and a decrease in lime close to their margins, changes probably related to the diffusion of material in and out of the marginal zones during the migmatitization of the enclosing rocks. The observed mineralogical variations appear, therefore, to be the result of essentially isochemical transformations. However, the changes in the water content and in the specific gravity are systematically related to the mineralogy; the former has minimum values and the latter maxima in the intermediate zones where the concentrations of granulite facies minerals are greatest.

It might be considered that these basic bands have been subjected to three consecutive phases of metamorphism, the effects of which penetrated successively less far into them. In the Ballymartin band, for example (Figure 3), the central hornblende rich assemblage could be considered to be the product of an early amphibolite facies phase the effects of which penetrated throughout the band; the intermediate hornblende-poor zones could be considered to have been produced during a later granulite facies phase, the effects of which did not penetrate all the way to the centre of the band; and the hornblende-rich marginal zones could be considered to represent a still later amphibolite facies phase which affected the band only peripherally. In the Port na Meidhaig band, although the overall metamorphic grade is higher, the occurrence of three phases of metamorphism could similarly be postulated.

However, if the marginal zone assemblages had, in fact, formed during a later phase of metamorphism, lower in grade than that which generated the assemblages of the intermediate zones, one would expect to find some textural evidence of diaphthoresis within them: coronae of kelyphite around garnets and the mantling of pyroxene grains by amphibole are commonly observed features in granulite facies basic rocks which have undergone retrograde metamorphism (Davidson, 1943). In the present case, although definite textural evidence as to the order of crystallization is lacking, features such as the embaying of hornblende grains by pyroxene, the occurrence of optically continous groups of hornblende inclusions in pyroxene grains and the rimming by finely granular ore of hornblende grains enclosed by clinopyroxene (Plate 8), all suggest that the pyroxene developed later than the hornblende. The formation of pyroxene and garnet at the expense of hornblende is considered to be an essential process in the petrogenesis of basic charnockitic rocks by Groves (1935), Quensel (1951), Compton (1957) and Parras (1958). Parras considers that the transformation, which he refers to as 'charnockitization', may be set out systematically as follows:

$$1)\ \text{hornblende} \xrightarrow[\text{of plagioclase}]{\text{with acidification}} \text{diopside}$$

2) diopside + plagioclase $\longrightarrow$ {hypersthene + garnet + secondary quartz

It is considered (Fyfe et al., 1958) that there exists a field of overlap between the lower subfacies of the granulite facies and the upper subfacies of the amphibolite facies such that, at the same temperature and pressure, granulite facies assemblages will be generated under 'dry' conditions and amphibolite facies assemblages under 'wet' conditions. Accordingly, rather than being the result of a polymetamorphic cycle, as discussed above, it may be that the variations in mineralogy within these bands reflect variations in the availability of water during a single period of recrystallization; the relatively hornblende-rich zones being portions of the bands where water was most freely available. Figures 3 and 5 therefore suggest that, during recrystallization, water was most abundant at the margins and near the centres of the basic bands and scarce in the intermediate zones.

This distribution of water may be explained by the following reasoning: Elevation of pressure and temperature to values conducive to the production of granulite facies assemblages would cause the expulsion of most of the water initially contained in these basic rocks. However, according to Sutton and Watson (1951), metamorphic changes affect the margins of basic bands first and move towards their centres from both sides. Therefore, it is possible that the expulsion of water from the central portions of the bands was not thoroughly accomplished and that sufficient was retained to permit the generation of the hornblende-rich central zones. Again, since the basic bands are enclosed by relatively 'wet' Banded Migmatite, it seems reasonable to presume that water vapour would penetrate at least a few feet into their marginal portions during metamorphism; the presence of such water would inhibit the crystallization of granulite facies minerals and permit the generation of the hornblende-rich marginal assemblages. The hornblende-poor condition of the intermediate zones may indicate that most of their initial water content was driven out during the elevation of the pressure and temperature and that they were not close enough to the margins of the bands to be contaminated by extraneous water vapour.

Bowes (1962) has said that in the Lewisian "..... (wet) migmatization stops abruptly against (dry) pyroxene-granulites": observations in these basic bands, however, suggest an intimate intergrading between the two.

Origin:

The transgressive contacts which the broad basic bands occasionally have against the enclosing Banded Migmatite (Plate 5), together with uniformity of chemical composition within them (Tables 5 and 6), strongly suggest that these bands originated as intrusive basic rocks which were emplaced prior to the main cycle of metamorphism, since the assemblages now observed within them, which are the normal products of high grade 'charnockitic' metamorphism of basic rocks (Gosh, 1941, Quensel, 1951, Parras, 1958), are believed to have been engendered during that cycle.

The basic lenses and blocks included in the Banded Migmatite, the mineralogical composition of which is illustrated in Table 4, are similar texturally and mineralogically to the marginal zones of the broad basic bands and may in part be fragments of narrow bands of intrusive basic rock which have been broken up by plastic movement of the enclosing migmatite. However, metamorphic convergence will result in the genesis of similar mineral assemblages and textures in rocks which are chemically similar but of diverse origin when they are subjected to the same metamorphic conditions (Poldervaart, 1953); it is therefore possible that some of these blocks and lenses may represent remnants of bands of sediments of appropriate composition which have been completely reconstituted mineralogically during metamorphism.

iii) Ultrabasic Inclusions.

The ultrabasic material occurs as dark greenish lenses and sub-angular to sub-rounded blocks most of which are not more than a few feet in width, although a few larger ones occur and one example over a hundred feet wide was observed and is discussed in detail below. In these ultrabasic lenses and blocks parallel elongation of the tabular minerals is often observed and sometimes there is some fine banding parallel to this direction of elongation. These directional structures in the ultrabasic rock are sometimes concordant with the banding of the enclosing Banded Migmatite but often, especially in the case of the smaller blocks, oblique to it; and groups of blocks can occasionally be observed, the members of which all appear to be randomly orientated with respect to each other. These groups are likely to represent larger ultrabasic bodies disintegrated by plastic movement of the enclosing rock. The mineralogical assemblages within some examples of these ultrabasic inclusions are illustrated in the accompanying table of modal analyses (Table 7).

In thin-section these ultrabasic rocks are found to have a generally equigranular texture with grains sizes ranging from 0.5 to 2.0 mm., but in bands very rich in either of the two major constituents, hornblende and diopside, elongate grains up to 10.0 mm. in length are sometimes observed. Features of the constituent minerals are noted below.

Hornblende: The hornblende is generally paler in colour than that observed in the basic inclusions described above. It shows well marked pleochroism with X - pale straw, Y - light green and Z - medium, sometimes slightly bluish, green, and is most often fresh. It forms generally sub-idioblastic grains which are sometimes embayed by, and occasionally have narrow reaction rims against, the diopside. Tiny ore grains often occur within the hornblende and it occasionally appears to contain grains of diopside which, however, because of their rounded form, are probably embayments rather than inclusions. Minor amounts of biotite occur as small flecks along cleavages within the hornblende and sometimes form a thin film between contiguous hornblende grains. The optical properties of some examples of the hornblende are included in Table 7. These properties suggest that the hornblende in those ultrabasic rocks is iron-poor and magnesium-rich as compared with that observed in the basic rocks included in the Banded Migmatite. (Deer et al., 1963)

Diopside: In most cases the diopside is colourless but it occasionally

Location of specimens:

T-159-b: Foreshore, 900 yds. west of the Green.

T-149-c: At Rudha Boraige Moire.

T-66-a : Foreshore, 600 yds. north of Traigh nan Gilean.

L-9-a : Foreshore at northernmost point on the Urvaig peninsula.

J-50-d : Foreshore, 50 yds. E.N.E. of the Ringing Stone.

A-32 : Foreshore, half a mile N.W. of Rudha Leacach.

	T-159-b	T-149-c	T-66-a	L-9-a	J-50-d	A-32
Hornblende	32.6	52.0	50.0	44.2	99.7	58.9
Clinopyroxene	28.3	46.2	49.6	42.4	0.3	28.5
Orthopyroxene	28.7	-	-	-	-	3.3
Biotite	1.7	0.1	0.1	9.4	-	3.1
Plagioclase	0.2	1.4	-	3.5	-	2.5
Quartz	-	-	-	tr.	-	0.6
Chlorite	1.3	-	-	-	-	3.2
Ore Minerals	6.0	0.4	0.3	0.5	-	-
Olivine	1.2	-	-	-	-	-

Hornblende -2V	86°	83°	82°	-	84°	80°
Hornblende $N\alpha$	1.638	1.647	1.650	1.640	1.649	1.638
Hornblende $N\gamma$	1.658	1.664	1.669	1.662	1.668	1.662
Clinopyroxene +2V	55°	55.5°	-	56°	-	56°
Clinopyroxene $N\alpha$	1.663	1.679	1.675	-	-	1.675
Clinopyroxene $N\gamma$	1.691	1.708	1.705	1.706	-	1.708

Table 7: Modal analyses of ultrabasic blocks and lenses and some optical properties of the principal constituents.

For location of specimens see opposite.

displays just perceptible pleochroism from colourless to very pale green. It forms xenoblastic to occasionally sub-idioblastic, generally equant grains which, as mentioned above, sometimes embay into and have reaction rims against hornblende and which often contain some small, frayed hornblende inclusions. Groups of these inclusions within individual diopside grains are sometimes optically continuous. The diopside is generally quite fresh and its optical properties, noted in Table 7, indicate that it lies in the diopside range of the diopside-hedenbergite series (Hess, 1949).

Orthopyroxene: Although orthopyroxene is often absent it makes up almost 30 per cent of some of the specimens examined. It is often fresh but in a few cases heavily altered to bastite, is weakly pleochroic with X and Y pale pink and Z colourless and forms xenoblastic to occasionally sub-idioblastic grains which sometimes contain inclusions of hornblende and diopside. The orthopyroxene in specimen T-159-b has the following optical properties, $-2V\ 87^{\circ}$, $N\alpha\ 1.664$, and $N\gamma\ 1.678$. These properties indicate that it lies in the enstatite range of Winchell's enstenite series (Winchell, 1951) and, therefore, has a low iron content.

Biotite: Minor amounts of biotite occur in many of the ultrabasic inclusions although it is sometimes completely absent. It is generally strongly pleochroic with X - yellow, Y - medium reddish brown and Z medium to dark reddish brown but occasionally pale, iron-poor, phlogopitic varieties occur. The biotite most often forms slender, sometimes rather ragged, laths which are often intergrown with hornblende and sometimes contain small inclusions of ore. Occasionally they are intergrown with larger ore grains. As mentioned above, minor amounts of biotite also occur along the cleavages within hornblende and as thin films between adjacent hornblende grains.

Plagioclase: The plagioclase forms fresh or very slightly sericitized, xenoblastic, interstitial grains which contain small laths of biotite and occasional small, rounded, hornblende inclusions. The composition of the plagioclase ranges from An_{25} to An_{40}.

In one of the specimens examined the plagioclase exhibits some unusual textural features (Specimen A-32). This rock consists of alternating hornblende-rich and diopside-rich layers. The plagioclase is for the most part confined to the former, where it occurs as somewhat lobate, skeletal grains which embay into the hornblende and against which the hornblende sometimes has narrow reaction rims. Although the plagioclase is fresh, it is rimmed and dissected by an irregular network of veins of light green serpentine. It is suggested that, in this case, the plagioclase formed at the expense of the hornblende, probably as the result of the metasomatic introduction of soda, and that the network of serpentine veins represent material from the hornblende which could not be incorporated in the plagioclase. Plate 9-A illustrates this textural relationship between the plagioclase and hornblende.

Olivine: Olivine occurs only very rarely as remnant grains which are embayed by adjacent pyroxene grains, dissected by irregular ore veinlets and partly or completely serpentinized.

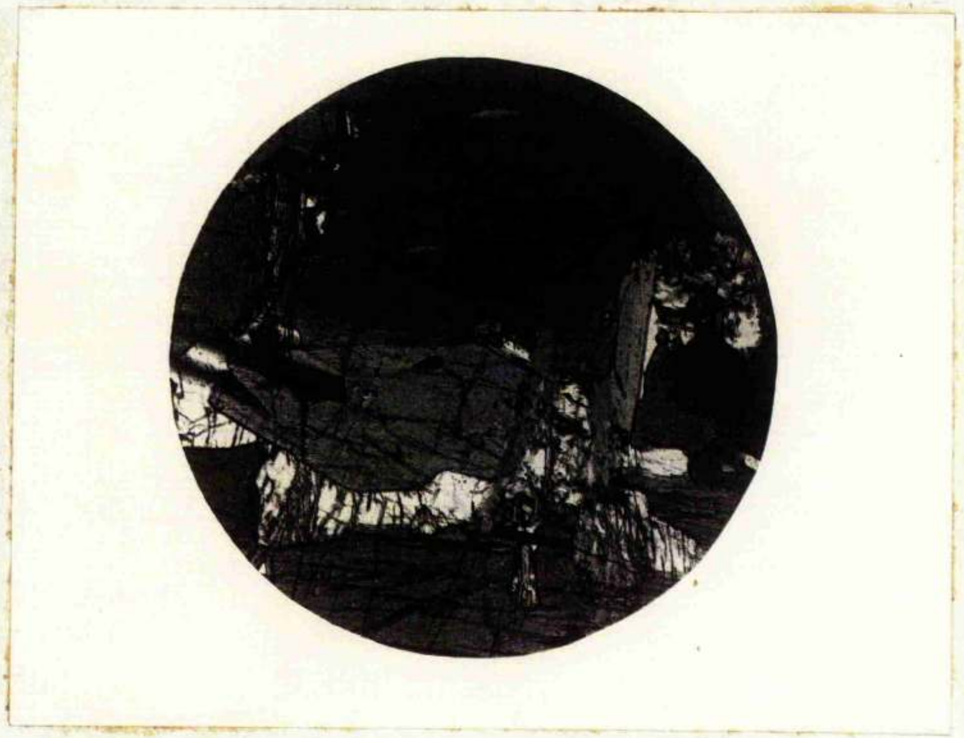
Ore Minerals: Ore minerals are present generally in only negligible

PLATE 9.

A. Lobate plagioclase grains embaying into hornblende in an ultrabasic lens at Rudha Leacach. An irregular network of serpentine stringers can be seen in the plagioclase. (X 15)

B. Inclusions of hornblende and ore in diopside. Marginal zone of the large ultrabasic lens at the Ringing Stone (X 60)

PLATE 9.



A.

B.

amounts as occasional irregular grains but sometimes occur more plentifully as small, generally equant grains scattered fairly evenly throughout the rock.

<u>Quartz:</u> There occur very occasional small, shapeless, interstitial quartz grains which are associated especially with hypersthene.

<u>Ultrabasic Lens at the Ringing Stone.</u>

A lens-shaped ultrabasic body much larger than the blocks and lenses discussed above is included in the Banded Migmatite near the Ringing Stone on the north shore between Balephetrish and Vaul. It is approximately 100' wide at its broadest part and some 300' long and is extended in a direction parallel to the banding of the enclosing rock which bulges out to accomodate it. The ultrabasic rock is generally mantled by a layer, several inches wide, of acid pegmatitic material which grades rapidly into the surrounding Banded Migmatite. Some blocks of ultrabasic material, believed to have been detached from the main body during plastic movement of the pegmatitic material, are seen 'floating' in this pegmatitic layer; an example is illustrated in Plate 6-B. At some points along the margin of the ultrabasic body the pegmatitic material is absent and the contact between the ultra-basic rock and the enclosing Banded Migmatite is seen to be gradational over several inches. At its western end the ultrabasic body is crushed and shattered and there is a profuse development of biotite within it.

Examination of several thin-sections of this ultrabasic body has revealed that its marginal zones are mineralogically and texturally very similar to the smaller lenses and blocks of ultrabasic rock discussed above but that in its central portion important amounts of heavily serpentinized olivine occur, constituting up to about fifty per cent of the volume of the rock. The hornblende and diopside are usually fresh but when in contact with or close to grains of serpentinized olivine they are dissected by ore-lined cracks radiating out from the olivine grains and are themselves slightly serpentinized. This suggests that the serpentinization of the olivine was an event later than the crystallization of the diopside and hornblende. Features of the individual constituent minerals are now briefly noted.

Hornblende: The hornblende is pleochroic in shades of pale green and forms xenoblastic to occasionally sub-idioblastic grains from 0.5 to 2.0 mm. in size, which are embayed by the diopside. Its optical angle, -2V, is 82°, and it has the following refractive indices: N α 1.649 and N γ 1.668.

Diopside: The diopside is colourless and forms xenoblastic to occasionally sub-idioblastic, generally equant grains from 0.5 to 2.5 mm. in diameter. These sometimes contain many tiny schiller-like ore inclusions and often, especially close to the margin of the body, contain irregular flecks of hornblende, all of which, within one diopside grain, are in optical continuity. Plate 9-B illustrates these inclusions in a diopside grain. In the detached blocks 'floating' in the pegmatitic mantle, the diopside still contains hornblende inclusions, although distinct grains of that mineral are absent, and it is sometimes rimmed by a narrow film of a pale green amphibole, especially when it abuts against biotite. The optical properties of the diopside, +2V 56°, N_{α} 1.668 and N_{γ} 1.698 indicate that it lies in the diopside range of the diopside-hedenbergite series (Hess, 1949).

Biotite: The biotite is a pale phlogopitic variety in the detached blocks but somewhat more strongly coloured in the marginal zone of the main body. It forms fresh, irregularly orientated laths up to about 2.0 mm. in length, which are free from inclusions except for occasional rods of ore along cleavages, and which sometimes appear to have formed at the expense of the hornblende.

Orthopyroxene: Although orthopyroxene is generally absent it occurs in minor amounts in occasional specimens from close to the margin of the ultrabasic body, forming xenoblastic to occasionally sub-idioblastic grains up to 1.0 mm. in length. These display faint pleochroism from colourless to pale pink and are often extensively altered, peripherally and along cleavages and cracks, to bastite. The optic angle, -2V, is 84°, which suggests that it lies in the hypersthene range of Winchell's enstenite series (Winchell, 1951), but extensive alteration to bastite prevents the measurement of the refractive indices to confirm this.

Olivine: Abundant olivine occurs in the central portion of this body but it is absent close to the margins. It forms irregularly outlined, somewhat embayed grains up to about 2.0 mm. in size which are either partly or wholly replaced by serpentine and dissected by narrow irregular ore veins. As well as the narrow veins of ore minerals, small discrete grains of ore are associated with the olivine in the central portion of the body but are generally absent in the marginal zones. The optic angle, -2V, of the olivine is 87°, indicating that it has a composition about fayalite$_{25}$forsterite$_{75}$.

Mineralogical and chemical changes within a series of samples taken along a line from the centre of the ultrabasic body to its northern margin were examined in some detail. The mineralogical changes observed are illustrated in Figure 6 and the chemical changes in Figure 7. Values from an adjacent detached block are included in these diagrams along with those from the ultrabasic body.

Metamorphic Facies and Origin.

The two principal constituents of the smaller ultrabasic lenses and blocks are hornblende and diopside which are accompanied by minor amounts of biotite, plagioclase and ore and occasional traces of quartz, chlorite and olivine. Varying amounts of orthopyroxene occur in a few examples. The combination of hornblende, diopside, and orthopyroxene is indicative of metamorphism in the hornblende granulite subfacies of the granulite facies (Fyfe et al., 1958). However, the frequent absence of the orthopyroxene indicates transition to the sillimanite-almandine subfacies of the almandine amphibolite facies, as does the presence of some biotite. Textural evidence suggests that the latter mineral has, at least in part, formed at the expense of the hornblende; it may have grown during an easing of conditions after the highest grade of metamorphism had been achieved.

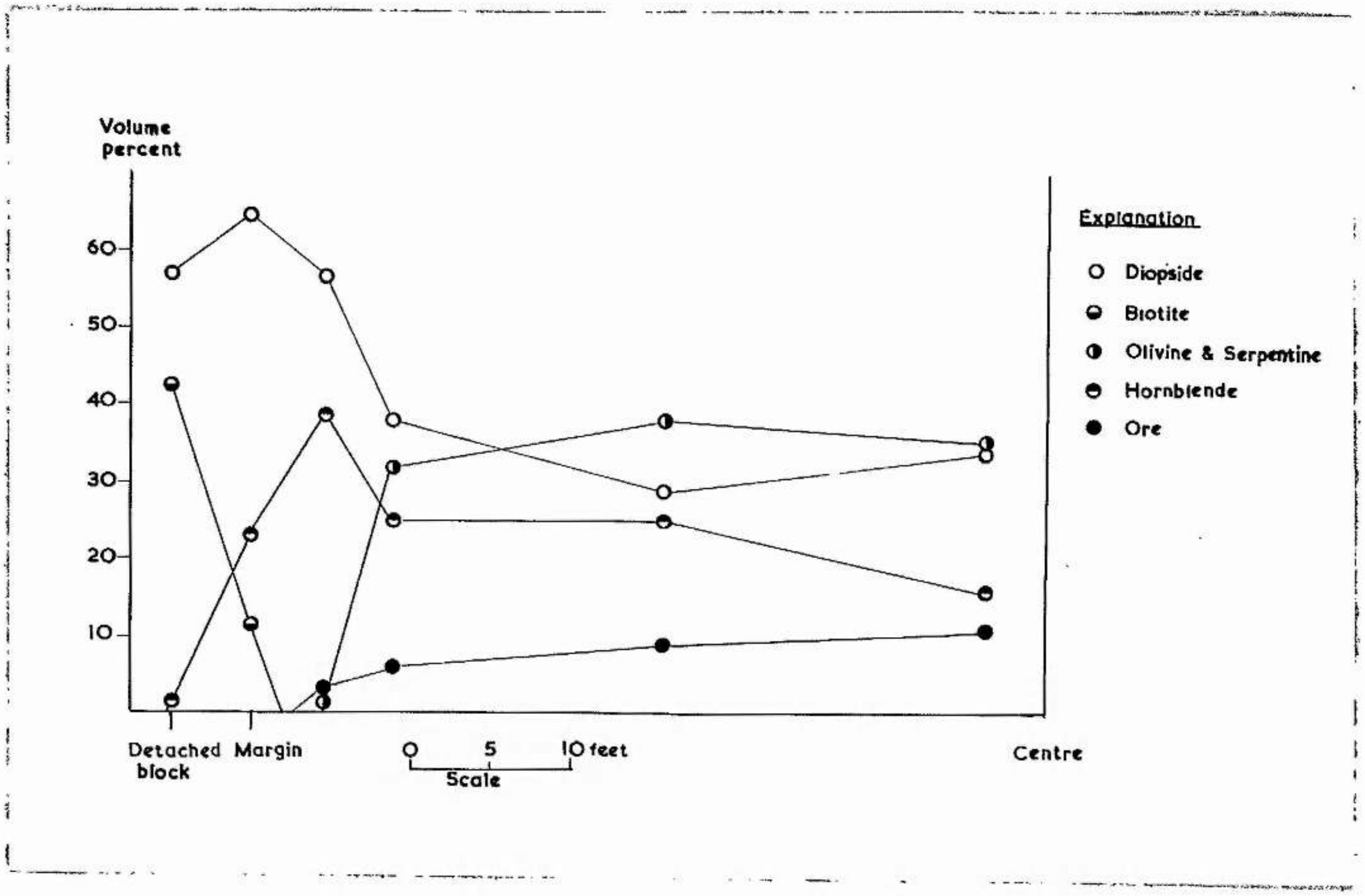
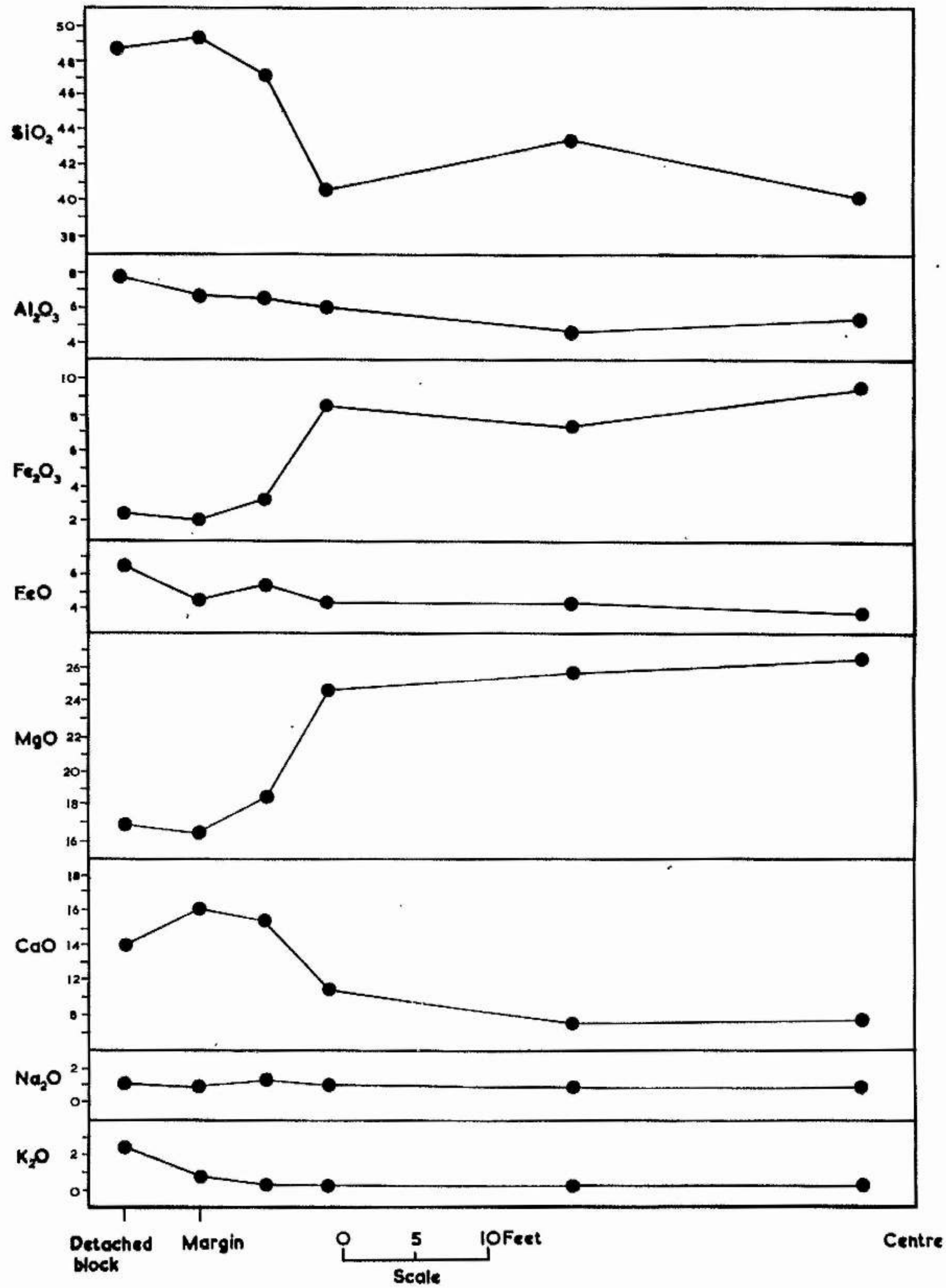


Figure 6: Diagram constructed from modal analyses to illustrate changes in the mineralogy within the large ultrabasic lens at the Ringing Stone between the centre and the northern margin at the broadest part. Values for an adjacent detached block, lying on the same line, are also included. The values for ore include the material which occurs as veinlets within the olivine and serpentine as well as that forming discrete grains.

Figure 7: Chemical variations within the series of specimens the mineralogy of which is illustrated in Figure 6. The values are given in weight per cent.



SiO2
Al2O3
Fe2O3
FeO
MgO
CaO
Na2O
K2O
50
48
46
44
42
40
38
8
6
4
10
8
6
4
2
6
4
26
24
22
20
18
16
18
16
14
12
8
2
0
2
0
Detached block
Margin
0
5
10 Feet
Scale
Centre

The assemblage in the marginal zone of the large ultrabasic lens at the Ringing Stone is similar to that in the small blocks. Orthopyroxene does not occur in the series of specimens featured in Figure 6 but it does occur occasionally in other specimens from the marginal zone and there is also occasional plagioclase.

In the centre of the large lens hornblende and diopside are still important constituents of the rock but there also occurs a considerable amount of heavily serpentinized olivine and of ore, the latter occurring as discrete granules and irregular veinlets. In the centres of certain large ultrabasic lenses in the Lewisian Complex of the North West Highlands, Sutton and Watson (1950) observed the preservation of peridotitic mineral assemblages; and it seems probable that the olivine-rich material in the core of this lens represents the relic of such an assemblage which has been partly converted to diopside and hornblende. In the marginal zone the conversion has been complete and none of the original olivine remains.

The chemical changes corresponding to the mineralogical changes observed are illustrated in Figure 7 and indicate that the marginal zone has been enriched in SiO_2, Al_2O_3, CaO and alkalies; and that MgO and Fe have been displaced from it. Some ten feet from the margin there exists a geochemical depression of SiO_2 which suggests that displacement inwards of MgO and Fe has caused the genesis of a 'basic front' at the inner limit of the contaminated marginal zone. It is reasonable to postulate the introduction of SiO_2 and alkalies from the surrounding rocks, probably while they were undergoing migmatitization and much migration of material was taking place.

That the ultrabasic rock should acquire CaO and Al_2O_3 from the Banded Migmatite seems less likely, at first sight; but textural evidence of replacement of plagioclase by potash felspar is observed within the latter rock and Sutton and Watson (1950), in their account of similar rocks from the Scourian division of the Lewisian, have suggested that the lime and alumina released by this process would probably migrate into nearby ultrabasic bodies.

As noted above, the diopside grains in the marginal zone contain dense patches of regularly orientated tiny ore inclusions and occasionally some optically continous groups of hornblende inclusions. It is suggested that the ore may represent iron trapped in the diopside grain during its crystallization at high temperature which later exsolved to give rise to the present mass of small inclusions. Similar inclusions were observed within diopside grains in an ultrabasic body at Union Bay, Alaska and a similar hypothesis to explain their origin suggested by Ruckmick and Noble (1959). The occurrence of the optically continous groups of hornblende inclusions suggests that the diopside formed later than the hornblende and, at least in part, at its expense; especially since diopside inclusions within hornblende grains are not observed. The partial replacement of hornblende by diopside was probably associated with the expulsion of water during the raising of the metamorphic grade. The minor amounts of pale amphibole observed rimming the diopside in the detached blocks suggest that a later easing of conditions or re-introduction of water permitted a small scale reversal of this process to take place.

Cracking and veining of diopside and hornblende grains when they abut against serpentinized olivine demonstrates that the serpentinization process occurred later than the main period of metamorphism and migmatitization. Sorensen (1954) believes that the formation of serpentine in ultrabasic bodies is probably related to weathering, for serpentinization is confined to the upper part of a large mass of dunite in the Ural Mountains; the serpentinization observed in the present case may therefore be a comparatively recent event unrelated to the metamorphic processes being discussed in this thesis.

The larger of these ultrabasic bodies are likely to have originated as intrusive or extrusive olivine-rich igneous rocks. The smaller lenses and blocks may in many cases be fragments of larger blocks disrupted by plastic movement of the migmatite and also be of ultimate igneous origin; however, some of them may be much altered fragments of calc-silicate metasedimentary bands which have been broken-up by plastic movement of adjacent rocks.

iv) Soda Rich Rocks at Creagan Mora.

About six hundred yards west of Creagan Mora on the north shore, between Balephetrish and Vaul, some basic rocks included in the Banded Gneiss possess unusual features which are deserving of special comment.

Within a band of weakly foliated basic rock some twenty feet broad there occur, singly or aggregated in large clusters, porphyroblasts of albite up to a foot in length. An example of one of the clusters of albite porphyroblasts is illustrated in Plate 10.

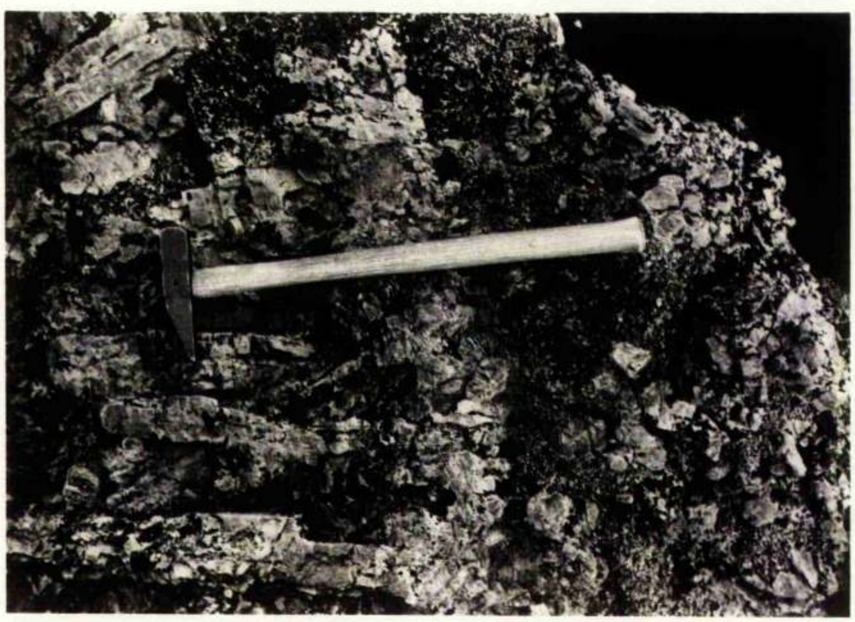
<u>PLATE 10.</u>

A. Cluster of albite porphyroblasts within basic gneiss at Creagan Mora.

B. Close-up view of the same.

PLATE 10.

A.



B.

The albite lies in the An_6 to An_{10} compositional range and in thin section it is seen to have weakly defined albite twinning and to be partly sericitized. It contains occasional groups of irregularly outlined antiperthitic potash felspar inclusions, and also some tiny, mutually parallel, laths of reddish brown material, perhaps rutile. A matrix composed of variously sized xenoblastic laths of clinopyroxene and finely granular calcite occurs within the clusters of albite porphyroblasts and a narrow film of potash felspar, in which cross-hatched twinning can sometimes be discerned, occasionally separates this matrix from the albite. The clinopyroxene is pale green and non-pleochroic. Its optical properties, $+2V\ 61^{\circ}$, $N\alpha\ 1.685$, $N\gamma\ 1.712$, are those of a salite (Hess, 1949).

The rock enclosing these clusters of albite porphyroblasts is weakly foliated and made up principally of plagioclase and hornblende. It has a xenoblastic granular texture with most grains lying within the 0.5 to 2.0 mm. size range. The plagioclase is generally fresh, though occasional grains have heavily sericitized cores, and it displays fairly well developed albite twinning. It is an oligoclase with a composition of An_{16}. The hornblende is pleochroic from pale straw to light brownish green and forms xenoblastic to occasionally sub-idioblastic grains which are generally elongated parallel to the foliation. It is fresh and free from inclusions and has the following optical properties, $-2V\ 77^{\circ}$, $N\alpha\ 1.659$, $N\gamma\ 1.678$. Colourless clinopyroxene occurs in minor amounts as xenoblastic grains intergrown with and containing inclusions of hornblende. There are very occasional small apatite grains and traces of ore. A modal analysis of an example of this rock is now given.

Mineral	Percentage
Hornblende	49.4
Plagioclase	48.9
Clinopyroxene	1.5
Apatite	0.1

Adjacent to this band of basic rock containing the albite porphyroblasts there occurs a band of fine to medium grained rock, the principal constituent of which is albite. The albite, which has a composition in the An_4 to An_{10} range, forms a xenoblastic granular mosaic of grains ranging from 1.0 to 2.0 mm. in size which are fresh and display very sharp and distinct albite twinning. An irregular network of fine red veinlets of ore, which at least in part is hematite, ramifies throughout the plagioclase mosaic; and fairly frequently there occur irregularly outlined, sometimes skeletal, ore grains mostly from 0.1 to 0.5 mm. in diameter. Small amounts of biotite sometimes cling to these ore grains. Xenoblastic, somewhat lath-shaped grains up to 1.0 mm. in length of pale yellow serpentine, in which a pattern of transverse cracks can often be discerned, are also of frequent occurrence. These serpentine grains, which may be much altered remnants of pyroxene or olivine, are sometimes rimmed by and intergrown with small amounts of pale blue amphibole. Occasional small sub-rounded apatite grains occur in this rock. A modal analysis is given below.

Mineral	Percentage
Albite	71.0

Ore	11.9
Serpentine	15.5
Biotite	1.4
Apatite	0.2

About a hundred feet inland there occurs a small outcrop of albite-rich gneiss, the relationship of which to the above rocks is not visible, in which some interesting textural features occur. The albite, the composition of which ranges from An_4 to An_8, is once again fresh and displays distinct albite and sometimes pericline twinning. It forms a mosaic of xenoblastic grains up to 1.5 mm. in diameter and constitutes some 70 per cent of the volume of the rock. Fresh biotite, pleochroic from pale to light brown, is the dominant dark mineral and forms narrow laths up to 2.0 mm. in length which are often aggregated into clusters and show some tendency to parallel orientation. Xenoblastic embayed grains of hornblende, pleochroic from pale to medium, slightly brownish green, are sometimes intergrown with the biotite; and there are, occasionally, some small, xenoblastic grains of colourless pyroxene associated with the hornblende and biotite. Small, sub-rounded grains of apatite occur in accessory amount, generally associated with the mafic minerals.

The most unusual and interesting feature of this rock, however, is the occurrence within it of small, vesicular like bodies made up of aggregations of quartz and calcite. These bodies, which may be up to 1.0 mm. in length, are variable in shape; they often have irregular lobate outlines but sometimes are sub-rectangular. Within them quartz forms xenoblastic grains up to about 0.1 mm. in diameter, while the calcite grains, which are of less frequent occurrence, may be up to 0.5 mm. in diameter. A row of very fine quartz grains often occurs around their margins. Whenever one of these bodies abuts against biotite, that mineral is clouded by fine, dark brown dust which gradually becomes less dense away from the contact with the 'vesicular' body. The quartz is generally unstrained or only very slightly strained: this suggests that the 'vesicles' must have originated or at least attained their present nature after the main cycle of deformation and metamorphism, since the quartz in the surrounding rocks is always markedly strained. Plate 11 illustrates examples of these 'vesicular' structures and a modal analysis of the rock containing them is given below.

Mineral	Percentage
Albite	68.1
Hornblende	2.5
Diopside	0.2
Biotite	27.2
Apatite	0.9
Quartz (in 'vesicles')	1.0
Calcite (" ")	0.2

Metamorphic Facies and Origin.

The occurrence of these albite-rich rocks and of the large albite porphyroblasts within a few yards of each other may indicate that, during migmatitization, soda became concentrated at this locality and caused the

PLATE 11.

A. 'Vesicular' structure in the albite rich gneiss at Creagan Morn. The 'vesicle' in this example is made up wholly of fine-grained quartz and is enclosed by felspar and biotite. The biotite displays the dark staining almost always observed when that mineral abuts against one of these structures. (X 60, crossed nicols)

B. An example of the 'vesicular' structures which contain calcite in addition to quartz. The calcite can be observed in left half of the picture. (X 60, crossed nicols)

PLATE 11.

A.

B.

abundant generation of soda-rich plagioclase. Alternatively these albite bearing basic rocks may have had a high initial content of soda, perhaps having originated as spilitic lavas, in which case it is only necessary to postulate localized migration of soda to form the albite porphyroblasts.

Harry (1952) has described migmatitic gneiss containing porphyroblasts of perthite from Glen Dessary and he considers that felspar porphyroblastesis there took place immediately after migmatitization when stress had declined but the temperature was still elevated and interstitial fluids still available to facilitate metamorphic diffusion. A decline of stress is deemed to be an essential prerequisite for felspar porphyroblastesis, for the solubility of felspar increases with increase in pressure.

The mineral assemblage in the basic rocks at Creagan Mora is: plagioclase; $\pm$ hornblende; $\pm$ biotite, with minor amounts of clinopyroxene and sometimes some ore and apatite. This assemblage is typical of the sillimanite-almandine subfacies of the almandine amphibolite facies (Fyfe et al., 1958) but in the basic bands within the Banded Migmatite already discussed, assemblages suggesting transition to the lower subfacies of the granulite facies are generally observed. It may be that after the main period of migmatitization, interstitial fluids promoted felspar porphyroblastesis, as suggested by Harry, and also caused partial diaphthoresis of the mineral assemblages in the basic rocks so that biotite and hornblende, rather than pyroxene and hornblende, are now the dominant mafic components. Alternatively, the amphibolite facies assemblage here may be symptomatic of a high initial water content.

v) Pegmatite.

The acid pegmatitic material, which occurs in parallel, sub-parallel and oblique bands and often mantles included blocks and lenses of basic and ultrabasic rock, is seen in section to be made up of quartz, microcline perthite and plagioclase, the relative proportions of which vary considerably, together with very minor amounts of hornblende, biotite, ore, serpentine, chlorite, zircon and apatite. Modal analyses of four examples of pegmatite bands are featured in Table 8.

The quartz forms irregularly outlined lobate grains which always display markedly strained extinction and are often traversed by trains of tiny bubbles. They occasionally contain groups of small, apparently randomly orientated, acicular inclusions; these are dark brown and may consist of rutile.

The potash felspar forms irregularly outlined, completely xenoblastic grains which are generally fresh and often show some cross-hatched twinning, although this feature is seldom very sharply developed. Perthitic inclusions of sodic plagioclase are common within the grains of potash felspar. These occur as small, regularly orientated blebs and as narrow tapering bands, and all of them, within a single potash felspar grain, are in optical continuity. Occasionally, as well as containing these inclusions, the potash felspar grains are rimmed by a narrow layer of sodic plagioclase, especially when they abut against quartz grains.

The plagioclase also forms irregular xenoblastic grains and is often sericitized to some degree. In occasional examples the plagioclase grains contain optically continuous groups of small anti-perthitic potash felspar

	J-40-f	T-42-a	T-66-b	T-159-a
Quartz	22.7	30.4	24.3	19.5
Perthite	70.5	48.0	33.7	23.1
Plagioclase	6.8	19.7	38.7	55.1
Biotite	-	0.4	1.7	1.6
Hornblende	-	-	0.1	-
Serpentine & Chlorite	-	0.5	1.5	-
Ore Minerals	-	0.9	-	0.5
Apatite	-	-	-	0.2
Zircon	-	0.1	-	-

Table 8: Modal analyses of examples of the acid pegmatite bands within the Banded Migmatite mass.

Location of specimens:

J-40-f : Adjacent to the large ultrabasic lens at the Ringing Stone.
T-42-a : East side of Eilean Ghreasamuill.
T-66-b : Foreshore, 620 yds. north of Traigh nan Gilean.
T-159-a: Foreshore, half a mile west of The Green.

inclusions which may be quite irregular in shape but occasionally have a sub-rectangular form. The larger plagioclase grains are generally free from myrmekitic quartz but it is often present in smaller grains enclosed by potash felspar. Albite twinning is frequently observed in the plagioclase, but is seldom very sharply developed, and there is occasionally some pericline twinning. Regularly orientated groups of dark brown acicular inclusions, similar to those observed in the quartz, occur occasionally in the plagioclase.

The biotite is pleochroic from light to medium or dark reddish brown. It forms occasional irregularly outlined laths which are sometimes partially chloritized. Hornblende, serpentine, chlorite and ore occur as very occasional small irregular grains and there are rare tiny, sub-rounded grains of zircon and apatite.

The presence of hornblende and biotite in small amounts in the pegmatite bands suggest that they formed under amphibolite facies conditions, but the paucity of mafic minerals prevents their assignation to any definite subfacies.

MASSIVE MIGMATITE.

1) Field Observations.

Migmatitic gneiss, somewhat different in character from the banded variety described above, occurs along the shore south of Ben Hynish. It is a massive rock in which banding is often indistinct or absent and in which basic and ultrabasic inclusions are of much less frequent occurrence than in the Banded Migmatite. When inclusions do occur they have gradational rather than sharp contacts with the enclosing rock. In the absence of well-developed banding there is a tendency for the mafic minerals to be aggregated in streaks and lenses, generally about a quarter of an inch in diameter, the parallel elongation of which gives rise to a steeply plunging lineation.

Eastwards, around Port na Meidhaig, and northwards, around Port Riseag, this massive rock passes gradually into the Banded Migmatite and there also occur occasionally, within the body of massive rock, zones of Banded Migmatite several feet in width with gradational contacts against the enclosing rock.

Plate 12-A illustrates the massive appearance of this variety of migmatite in the field.

2) Texture and Mineralogy.

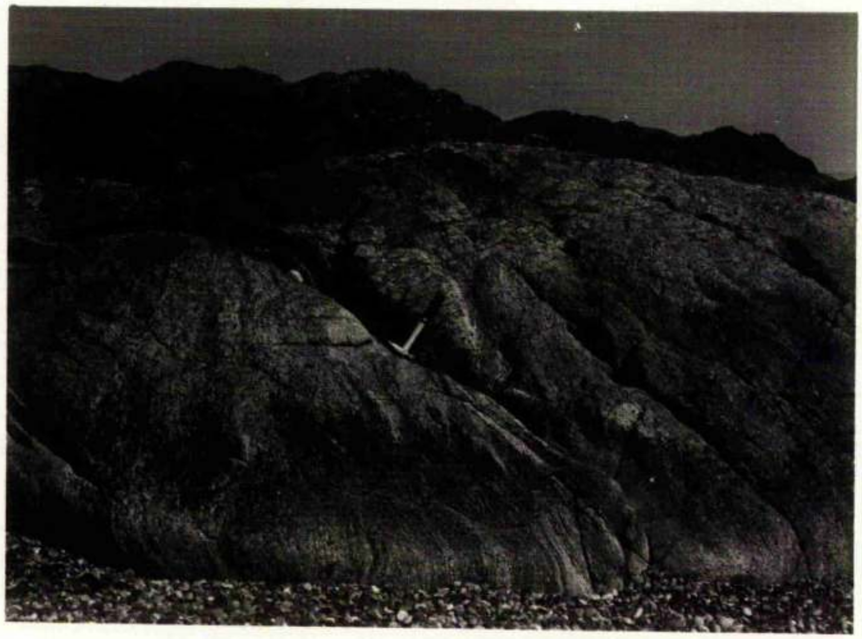
The dominant mafic constituents are orthopyroxene, clinopyroxene and hornblende; and minor amounts of biotite are generally present. The leuco-

PLATE 12.

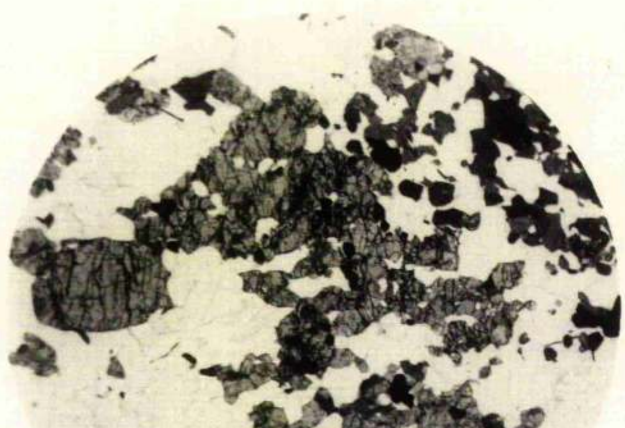
A. Massive Migmatite on the shore at Port Riseag.

B. Cluster of mafic minerals in Massive Migmatite. Made up of orthopyroxene and clinopyroxene with minor amounts of fine grained hornblende, especially in the top right hand quadrant of the picture, and occasional ore granules. (X 15)

PLATE 12.



A.



B.

cratic minerals, which constitute the bulk of the rock, are plagioclase, potash felspar and quartz; ore, apatite and zircon occur in accessory amounts.

The texture is xenoblastic granular with felsic minerals forming grains up to 3.0 or 4.0 mm. in diameter while the dimensions of the mafic minerals seldom exceed 2.0 mm. and are often less than 1.0 mm. The aggregation of the mafic mineral grains into irregular clusters several millimetres in diameter is a fairly well developed textural feature and one such cluster is illustrated in Plate 12-B. Within each of these clusters one or other of the two varieties of pyroxene is dominant while the other pyroxene and hornblende occur in subsidiary amounts.

In zones transitional to the Banded Migmatite hornblende and biotite replace the two pyroxenes as the dominant mafic constituents and banding replaces clustering as the mode of segregation of the mafic grains.

The accompanying table of modal analyses (Table 9) illustrates the sort of mineralogical variation encountered within the Massive Migmatite.

Characteristics of the individual minerals are described below.

Orthopyroxene: The irregular, xenoblastic laths of orthopyroxene are generally crossed by irregular cracks and often partly, and sometimes completely, altered to an aggregate of fibrous material and granular ore, the alteration commencing peripherally and along cracks. Fresh grains show well marked pleochroism, X - salmon pink, Y - pale pink, Z - colourless, but in the unaltered cores of partially altered grains pleochroism is weak. The orthopyroxene grains occur in clusters in which they are intergrown with

	T-130	T-131	T-132	H-1	H-2	H-68	H-70-b
Hornblende	0.6	29.1	0.3	3.7	9.0	8.1	-
Clinopyroxene	-	-	0.1	6.9	14.3	1.2	-
Orthopyroxene	4.0	1.0	4.0	1.4	11.8	0.4	-
Biotite	0.2	6.7	0.6	0.1	0.7	1.7	1.0
Plagioclase	68.1	46.4	82.7	49.7	57.3	43.6	40.9
Potash felspar	23.7	10.5	9.7	34.1	4.9	24.9	30.3
Quartz	2.1	1.5	0.6	1.9	0.8	19.1	26.4
Ore	1.0	3.3	1.2	0.9	1.2	0.2	0.1
Apatite	0.2	1.4	0.4	0.4	0.1	0.8	tr.
Chlorite & Serpentine	-	-	0.5	1.0	-	-	1.3
Zircon	tr.	-	tr.	tr.	tr.	-	-

Table 9: Modal analyses of specimens of the Massive Migmatite.

Location of specimens:

T-130 : Foreshore at Dun Hiader.
T-131 : Foreshore, 900' west of Port na Meidhaig.
T-132 : Foreshore, 750' west of Port na Meidhaig.
H-1 : 250° S.10°W. of Dun Hiader.
H-2 : Same locality as H-1.
H-68 : Foreshore at Port Riseag.
H-70-b: Foreshore, 950' south of Port Riseag.

minor amounts of clinopyroxene and hornblende and they sometimes contain small inclusions of the latter mineral. Oblique extinction and zoning are commonly observed and fine lamellae parallel to the c - axis sometimes developed. Similar lamellae in orthopyroxene in the Intermediate Gneiss of Ben Hough are described and their nature discussed later in this thesis (q.v., p. 144). The optic angle, $-2V$, ranges from 52° to 57° and N γ is 1.715, properties which indicate a fairly iron-rich hypersthene (Hess, 1949).

Clinopyroxene: Clinopyroxene is of rather sporadic occurrence. It forms xenoblastic grains congregated in irregular clusters which are generally fresh but sometimes slightly chloritized and which occasionally contain small inclusions of hornblende, little groups of which are sometimes optically continuous. The clinopyroxene is pale green in colour and occasionally displays very faint pleochroism from pale green to pale pinkish green. The optical properties, $+2V$ 58° to 60°, N α 1.687 and N γ 1.715, are those of a salite (Hess, 1949).

Hornblende: The hornblende is a variety pleochroic from straw to medium brownish green. It occasionally forms clusters of sub-idioblastic grains up to 0.75 mm. in size but more often occurs as smaller, irregularly outlined and embayed grains with somewhat frayed edges which are intergrown with, and sometimes included by, pyroxene grains. It also occurs in intergrowths with grains of biotite and ore and contains inclusions of the latter mineral and irregular patches of dark brown staining. Most often the hornblende grains are fresh but occasional grains are partially converted to pale green chlorite containing finely granular ore. The optic angle, $-2V$, ranges from 70° to 73° while N_{α} ranges from 1.658 to 1.662, N_{γ} from 1.679 to 1.681 and the birefringence from 0.019 to 0.021.

<u>Plagioclase</u>: Plagioclase forms xenoblastic grains up to 3.0 or 4.0 mm. in size which are generally only very slightly sericitized. They display rather weakly defined albite and sometimes pericline twinning and often contain some small rounded grains of potash felspar which are probably protuberances of lobate grains of that mineral rather than true inclusions. Frequently the plagioclase also contains groups of tiny dark brown needles which sometimes appear to be randomly orientated but are more often arranged in regularly orientated groups; two directions of orientation can sometimes be observed within a single plagioclase grain. When the plagioclase abuts against or is enclosed by potash felspar, it sometimes contains some myrmekitic quartz intergrowths.

<u>Potash Felspar</u>: The amount of potash felspar present varies from five to thirty per cent of the volume in examples of this rock. When present in small amounts it forms shapeless interstitial grains which insinuate themselves between and embay into the plagioclase, but when present more abundantly it forms xenoblastic grains of the same order of size as those of the plagioclase. These larger grains contain some perthitic inclusions of sericitized plagioclase and also some slender tapering ribbons of fresh albite. Only occasionally does the potash felspar display any trace of cross-hatched twinning but it always has very irregular shadowy extinction. The optic angle is negative and ranges from 70° to 83°.

<u>Quartz</u>: In most examples quartz occurs in only small amounts as

shapeless, interstitial blebs associated with the mafic minerals, but it occasionally occurs in substantial amounts forming large, lobate grains which embay into the felspar and contain inclusions of it. The quartz displays strained extinction and the larger grains are crossed by sub-parallel trains of minute bubbles.

Reddish-brown biotite, sometimes partially chloritized, and ore minerals occur in minor amounts and are sometimes intergrown together; the biotite is also sometimes intergrown with the hornblende.

Small, sub-rounded grains of apatite are fairly common and there are rare tiny grains of zircon and epidote.

The mineralogical and textural features of this rock are somewhat analogous to those of the intermediate members of the charnockite series of southern India, as summarized by Pichamuthu (1953). The list of minerals composing the intermediate charnockites given by Pichamuthu corresponds to the assemblage described above, while the characteristics of the individual minerals are similar to those described by him. The textural features considered typical of the Indian rocks are: the occurrence of micro-perthitic felspar intergrowths; the presence of 'quartz de corrosion' (myrmekitic quartz intergrowths in plagioclase); the frequent lack of twinning in plagioclase; the aggregation of the ferromagnesian silicates in microscopic patches; and the occurrence of minute, acicular inclusions, believed to be of rutile, in the quartz and plagioclase grains. Most of these features are developed to some extent in the Tiree rock but twinning in the plagioclase is not absent, although often weakly defined, and the acicular inclusions are present only in the plagioclase rather than in both quartz and plagioclase as is the case in the Indian rocks.

3) Metamorphic Facies.

The mineral assemblage in the Massive Migmatite is: oligoclase; potash felspar; quartz; orthopyroxene; clinopyroxene; hornblende, with minor biotite and accessory ore, apatite and zircon. The association of the two pyroxenes and hornblende is indicative of crystallization in the hornblende granulite subfacies of the granulite facies (Fyfe et al., 1958). Biotite would not be expected to appear in assemblages of this subfacies and the presence of small amounts of it, generally intergrown with grains of pyroxene or hornblende, probably indicates slight retrograde metamorphism after equilibrium at the granulite facies level had been attained. Such diaphthoresis is common in rocks of high metamorphic grade (Turner, 1948).

The Massive Migmatite grades into the Banded Migmatite in which an assemblage typical of the sillimanite-almandine subfacies of the almandine amphibolite facies is found and zones occur within the body of massive rock containing a similar assemblage.

CONTORTED MIGMATITE.

The Contorted Migmatite occurs at two localities which are discussed separately below.

(I) CREAGAN MORA.

1) Field Observations.

At Creagan Mora, on the north coast of Tiree between Balephetrish and Vaul, Contorted Migmatite occurs as a band which is three hundred yards wide on the shore but narrows rapidly inland and is enclosed on either side by Banded Migmatite.

It is a fairly massive, light to medium grey rock with buff coloured weathered surfaces and often has a streaky rather than a banded appearance. Irregular contortion of the streaks and bands within this rock is commonly observed and is illustrated in Plate 13-A. Occasional basic lenses occur within this rock but they are much less common than in the Banded Migmatite and they generally grade into the enclosing rock, whereas the basic inclusions in the Banded Migmatite usually have sharp boundaries.

A band of basic rock some fifty feet wide runs through this body of Contorted Migmatite. It trends in an approximately north-easterly direction and is often penetrated and broken up into blocks by pegmatitic material. The pegmatite has sharp contacts against the basic rock but most often grades into the surrounding migmatite. The basic band has a weak foliation

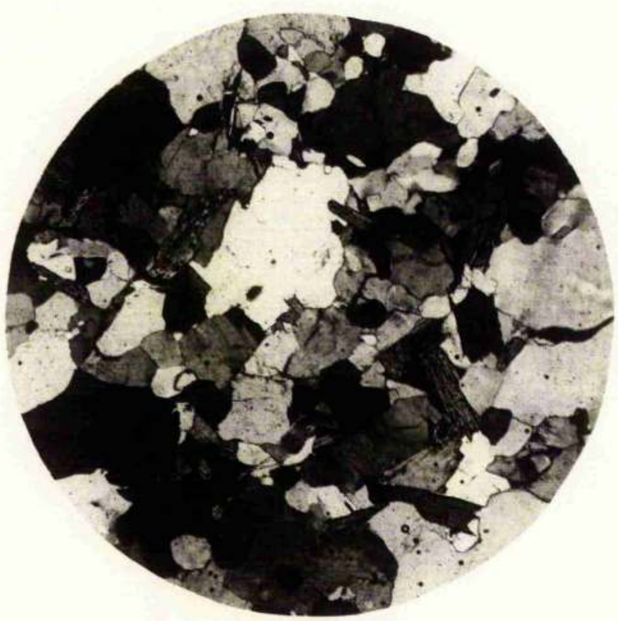
PLATE 13.

A. Contorted Migmatite at Creagan Mora.

B. Texture of the Contorted Migmatite. Small biotite laths can be seen in a xenoblastic mosaic of felspar and quartz. (X 15, crossed nicols)

PLATE 13.

A.



B.

which is generally more or less parallel to its margins, but when it is broken up into blocks by the pegmatite the direction of foliation varies in the several blocks.

2) Texture and Mineralogy.

i) Contorted Migmatite

ii) Basic Band

i) Contorted Migmatite.

This rock is made up predominantly of plagioclase and quartz with minor amounts of potash felspar and biotite, and accessory amounts of chlorite, apatite and ore.

The felspars and quartz make up an interlocking mass of completely xenoblastic grains ranging in size from 0.2 to 2.5 mm. in which are set narrow laths of biotite up to 1.5 mm. in length which show only a weak tendency to parallel elongation. The texture of this rock is illustrated in Plate 13-B.

Plagioclase, an oligoclase with a composition of An_{24}, is the dominant felspar and forms generally larger individuals than those of potash felspar. The plagioclase is sometimes slightly sericitized and shows some weakly developed albite twinning. It occasionally contains groups of tiny antiperthitic potash felspar inclusions and, when it abuts against potash felspar grains, some inclusions of myrmekitic quartz. Groups of mutually parallel small brown rods sometimes occur within the plagioclase grains.

These were also observed in the plagioclase grains of the Banded Migmatite and the Massive Migmatite.

The potash felspar forms fresh, irregularly outlined grains which occasionally show some traces of cross-hatched twinning. It often embays into the plagioclase and contains small plagioclase grains which are in optical continuity with adjacent large grains of that mineral.

The quartz occurs in irregularly outlined lobate grains which show well marked strained extinction.

The biotite is a variety pleochroic from pale to medium brown and is occasionally partly chloritized.

There are occasional laths of pale green chlorite which may perhaps be pseudomorphs after hornblende.

Modal analyses of two examples of this rock and a chemical analysis of one of them are given in Table 10.

ii) <u>Basic Band</u>.

The rock composing the basic band within the Contorted Migmatite at Creagan Mora has a xenoblastic texture with the constituent grains ranging in size from 0.25 to 2.0 mm. It is made up of brownish green hornblende with an optic angle, $-2V$, of 70°, pale green clinopyroxene with an optic angle, $+2V$, of 56°, completely sericitized plagioclase, and some interstitial quartz grains. Some small frayed inclusions of hornblende occur within the pyroxene and there are accessory amounts of ore minerals. There appears to be little variation in the mineralogy throughout this band and a modal

	J-56-a	J-58-c
Biotite	9.2	12.9
Plagioclase	57.0	62.1
Potash Felspar	8.1	6.9
Quartz	24.3	17.1
Ore Minerals	0.1	0.8
Apatite	0.3	0.4
Chlorite	1.0	-

	J-56-a
SiO_2	69.50
Al_2O_3	15.30
Fe_2O_3	0.40
FeO	1.84
MgO	1.82
CaO	2.54
Na_2O	4.75
K_2O	1.55
TiO_2	0.16
MnO	0.03
P_2O_5	0.04
H_2O+	1.07
CO_2 etc.	0.17
Total	99.17

Table 10: Modal analyses of two specimens of the Contorted Migmatite at Creagan Mora, and a chemical analysis of one of them. (Analyst: I.G.L. Sinclair)

analysis of an example is given below.

Mineral	Percentage
Hornblende	52.5
Clinopyroxene	7.0
Sericitized Felspar	27.8
Quartz	10.8
Ore Minerals	1.9

3) Metamorphic Facies.

The mineral assemblage in the Contorted Migmatite at Creagan Mora is plagioclase; quartz; potash felspar; biotite, with minor amounts of ore and apatite, while the assemblage in the basic band is plagioclase; hornblende; diopside; quartz. These assemblages suggest that these rocks should be assigned to the highest subfacies of the amphibolite facies, the sillimanite-almandine subfacies, while the occurrence of some anti-perthitic structures in the plagioclase of the migmatite confirms that high grade metamorphic conditions prevailed during the crystallization of felspar. An analysis of a specimen of the Contorted Migmatite from Creagan Mora is plotted on an ACF diagram for the sillimanite-almandine subfacies in Figure 8. From its position on that diagram it would be expected that garnet rather than biotite would be the dominant mafic component if, in fact, it had been metamorphosed under sillimanite-almandine subfacies conditions. However, as noted above when discussing the Banded Migmatite (q.v., p. 43), the occurrence of abundant biotite, rather than the almandine suggested by the ACF diagram, has

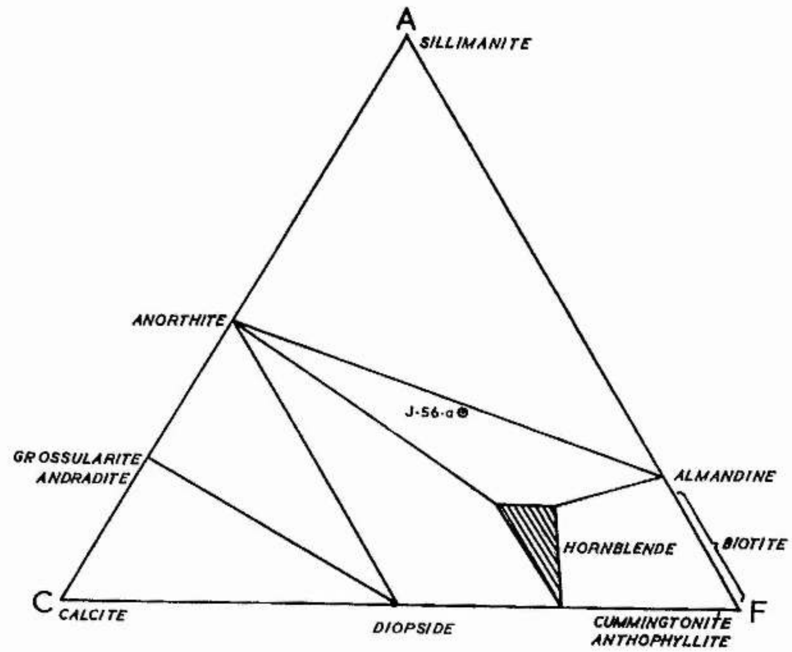


Figure 8: Plot of the analyzed specimen of the Contorted Migmatite on the ACF diagram for the sillimanite-almandine subfacies of the amphibolite facies. (Diagram after Fyfe et al., 1958)

also been noted in amphibolite facies rocks by Wahlstrom and Kim (1959). These workers believe that this may be due either to a low FeO/MgO ratio in the rocks or to diaphthoretic replacement of almandine by biotite. Physical conditions prevailing during metamorphism may also have favoured the genesis of biotite rather than garnet.

(II) HYNISH.

1) Field Observations.

The other occurrence of Contorted Migmatite is at Hynish on the south coast of Tiree where it makes up a body approximately a quarter of a mile broad and one mile long which is bounded on the south-east by the sea and on the north-west side grades into Banded Migmatite. Like the Contorted Migmatite at Creagan Mora, the rock here has a buff colour on weathered surfaces and the bands and streaks of dark material within it are generally very contorted. Irregular, sometimes sub-rounded, blocks of dark grey rock up to about two feet in diameter are included in the Contorted Migmatite; these blocks often possess weak foliation the direction of which, generally, does not coincide with the direction of the bands and streaks in the enclosing rock. The massive field appearance of this phase of the migmatites is shown in Plate 14-A and some of the included, dark grey blocks can also be discerned in that photograph. Plate 14-B illustrates the Contorted Migmatite at Hynish Pier about twenty or thirty yards from the passage into the Banded Migmatite; at this location the direction of the banding is fairly

PLATE 14.

A. Contorted Migmatite at Hynish Observatory. One of the included, sub-rounded blocks of fine grained hypersthene-bearing rock can be seen above the end of the hammer shaft.

B. Contorted Migmatite at Hynish Harbour.

PLATE 14.

A.

B.

regular although it is still rather streaky in nature.

A north-east trending basic band, some forty feet wide with near vertical margins, occurs within this body of Contorted Migmatite on the shore at Traigh Balbhaig, three quarters of a mile west of Hynish Farm. It has sharp contacts with the enclosing rock and there is some shattering and minor slickensiding along its margins, suggesting that they have been planes of movement.

2) Texture and Mineralogy.

i) Contorted Migmatite

ii) Basic Band

i) Contorted Migmatite.

The Contorted Migmatite at Hynish differs from that described above at Creagan Mora in that, in addition to the minerals noted there, it contains some garnet and hypersthene. The garnet occurs in very irregular amounts throughout the rock mass but the hypersthene is most often confined to the included dark blocks. Modal analyses of several examples of this rock are given in Table 11.

Plagioclase, an oligoclase in the An_{20} to An_{30} compositional range, is the dominant constituent and generally makes up more than half of the volume of the rock. It forms xenoblastic grains up to 2.0 mm. in size which generally are fresh but sometimes slightly sericitized; they display albite and sometimes pericline twinning. In the few examples in which potash felspar

	28	29	R-59-a	R-59-b	T-106
Plagioclase	64.2	51.6	29.6	0.8	59.3
Quartz	18.5	5.6	44.6	79.3	23.4
K-Felspar	1.5	10.1	0.3	0.6	9.7
Biotite	10.4	15.3	10.0	18.8	0.3
Orthopyroxene	4.7	-	4.5	-	7.3
Garnet	0.5	15.2	10.5	-	-
Chlorite	0.2	0.6	-	-	-
Sphene	-	-	-	0.3	-
Ore Minerals	0.1	1.5	0.5	0.2	0.1

Table 11: Modal analyses of examples of the Contorted Migmatite from Hynish.

Location of specimens:
28 : Foreshore, 340 yds. south of Hynish farm.
29 : Foreshore, 625 yds. south-west of Hynish farm.
R-59-a: 580 yds. east of Hynish Quarry.
R-59-b: From the same location as R-59-a.
T-106 : 400 yds. S.10°W. of the quarry.

occurs in significant amounts, the plagioclase felspar contains some myrmekitic intergrowths of quartz when it abuts against the potash variety.

Potash felspar occurs in variable amounts, forming from one to ten per cent of the volume of the rock, and is generally absent, or present in only accessory amounts in the dark included blocks. It forms interstitial, xenoblastic grains from 0.1 to 0.5 mm. in size which are fresh, generally have undulose extinction and sometimes display weakly developed cross-hatched twinning. Occasionally there are some slender, tapering, perthitic plagioclase inclusions in the potash felspar.

The amount of quartz present is also very variable, ranging from one to about eighty per cent of the volume, and it occurs most abundantly in the included blocks. It forms irregularly outlined lobate grains ranging in size from 0.1 to 6.0 mm., the larger being elongated parallel to the weakly developed banding of the rock. The quartz always shows heavily strained extinction.

Biotite is ubiquitous but the amount present is very variable. It is strongly pleochroic from pale to deep reddish brown and forms slender laths up to about 1.0 mm. in length which occur singly or aggregated in irregular clusters and are often associated with garnet when that mineral is present. The biotite is fresh and free from inclusions except for occasional flecks of ore.

The garnet is very pale purple in thin-section and forms grains up to about 2.0 mm. in size. These are often irregular and somewhat skeletal in outline, but occasionally are sub-rounded with entire margins. Poeciloblastic inclusions of quartz, biotite, and plagioclase are common in the garnet and it also contains occasional specks of ore. The refractive index of the garnet is 1.785 and in composition it is probably dominantly almandine.

The hypersthene occurs especially in the dark blocks and when it occurs outwith these blocks it is generally partially serpentinized. It forms irregularly orientated, xenoblastic laths up to about 0.5 mm. in length which are often colourless but sometimes show just perceptible pleochroism from colourless to pale pink; they are crossed by many irregular cracks along which serpentinization commences. The optical properties, $-2V\ 50^{\circ}$, $N\alpha\ 1.694$, and $N\gamma\ 1.715$, indicate that this is a rather iron-rich variety of hypersthene (Hess, 1952).

ii) <u>Basic Band.</u>

Variations in the mineralogical composition across the forty feet wide basic band which runs through the Hynish Contorted Migmatite mass at Traigh Balbhaig are illustrated in Figure 9. In the two basic bands within the Banded Migmatite, discussed in detail above (q.v., pp. 43-66) the distribution of the constituent minerals was seen to be more or less symmetrical and a garnet free zone two or three feet broad along their margins was noted. In the present case, however, the minerals do not have a symmetrical distribution for, although there is a garnet free zone along the west margin, the highest observed concentration of garnet occurs only a few inches from the east margin. Field evidence indicates that shearing has taken place along

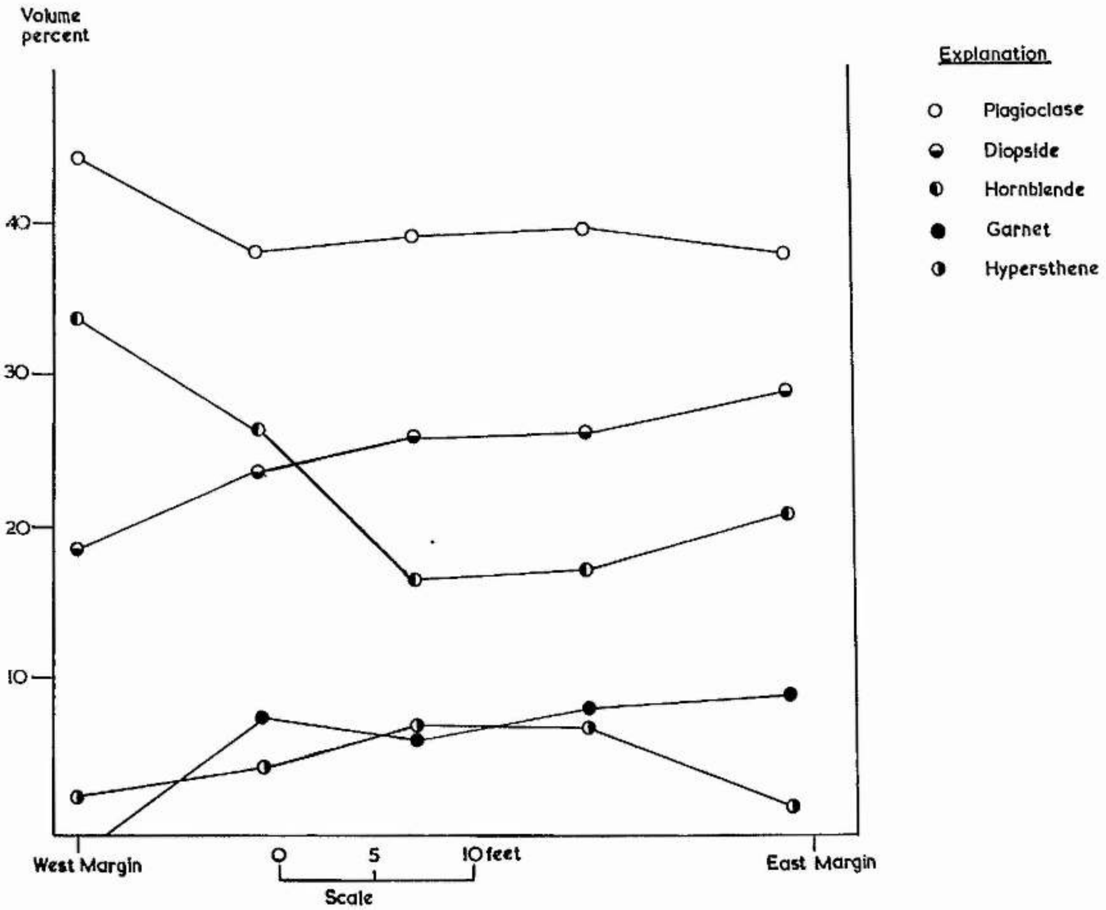


Figure 9: Variations in the mineralogical composition of the basic band included in the Contorted Migmatite at Traigh Balbhaig.

the contacts of this basic band: it may be, therefore, that the distribution of minerals was at one time symmetrical, with a garnet-free, hornblende-rich zone at the east margin as well as the west; the present absence of a garnet-free eastern margin being perhaps due to shearing having removed a few feet of rock from that side of the band. Evidence from the marbles and associated rocks at Balephetrish noted elsewhere in this thesis, and the existence of the flinty crush band in the north-west corner of the island, show that post-metamorphic movements did affect these rocks, most probably while they were under high pressure since flow lines were developed in the marbles; the shearing of the margins of this basic band may have been effected during the same period of movement.

Microscopically, the rock composing this basic band is seen to have a generally xenoblastic, granular texture with occasional garnets showing sub-idioblastic form. Most of the constituent grains lie in the 0.5 to 1.5 mm. size range but there are occasional plagioclase individuals up to 3.0 mm. in length. Bands of crushing and granulation occur close to the east margin and the mafic minerals within these bands, or close to them, are often partially or completely serpentinized. Descriptive notes on the constituent minerals are given below.

Plagioclase: The dominant mineral throughout this basic band is plagioclase. It forms xenoblastic grains which vary in size from 0.5 to 3.0 mm. and which often embay into hornblende and pyroxene grains. Albite twinning is often well developed and normal zoning is a commonly observed feature, while sericitization is absent or confined to the centres of grains. The plagioclase is labradorite with a composition ranging from An_{58} to An_{66}.

Garnet: The garnet is a very pale pink variety which forms sub-idioblastic grains containing inclusions of hornblende, clinopyroxene, plagioclase, quartz and ore. Its refractive index is 1.775 and its specific gravity 3.96, properties which indicate that it is an almandine-pyrope containing about fifty five molecular per cent of pyrope (Winchell, 1951).

Hornblende: In this rock the hornblende is brown in section, with no trace of green colouration, and is strongly pleochroic with X - brownish yellow, Y - light brown and Z - deep chocolate brown. It forms xenoblastic grains which are sometimes embayed by plagioclase and often intergrown with the pyroxenes. The hornblende is generally free from inclusions but small flecks of hornblende occur within grains of clinopyroxene and orthopyroxene and little groups of these, within a single pyroxene grain, are sometimes in optical continuity. Optical properties of the hornblende are $-2V\ 75^{\circ}$, $N\alpha$ 1.663 and $N\gamma$ 1.687.

Clinopyroxene: The clinopyroxene is a colourless variety which forms xenoblastic equant grains and, apart from the flecks of hornblende mentioned above, is free from inclusions. Its optical properties, $+2V\ 53^{\circ}$, $N\alpha$ 1.678 and $N\gamma$ 1.707, place it on the boundary between the diopside and salite ranges in the diopside-hedenbergite series. (Hess, 1949)

Orthopyroxene: The orthopyroxene is often colourless but sometimes shows faint pleochroism from colourless to pale pink. It forms xenoblastic laths which are often intergrown, sometimes iso-axially, with the clino-pyroxene and are often traversed by irregular cracks along which there is some alteration to bastite. The -2V of the orthopyroxene is 53° and it is, therefore, probably an iron-rich hypersthene.

Quartz: Very minor amounts of quartz occur as small, shapeless, interstitial grains with somewhat strained extinction, which are associated especially with garnet and hypersthene.

Accessory amounts of ore and apatite occur throughout the band and there are very occasional tiny grains of scapolite with moderate birefringence. Some irregular grains of epidote occur within the more highly sericitized plagioclase grains.

3) Metamorphic Facies.

At Hynish the assemblage in the Contorted Migmatite is plagioclase; quartz; potash felspar; biotite; ± almandine; ± hypersthene, with accessory sphene and ore. The assemblage in the dyke-like basic band is plagioclase; clinopyroxene; hornblende; almandine-pyrope; orthopyroxene, with accessory amounts of apatite, ore, quartz and scapolite.

The assemblage in the basic band is characteristic of the hornblende granulite subfacies of the granulite facies (Fyfe et al., 1958) while that in the migmatite appears to lie on the threshold between the amphibolite and granulite facies and equilibrium has apparently not been achieved within it; for, according to Ramberg (1952), the following reaction goes to the right under granulite facies conditions and to the left when amphibolite facies conditions prevail.

$$3SiO_2 + \underset{\text{biotite}}{K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} \qquad \underset{\text{potash felspar}}{KAlSi_3O_8} + \underset{\text{hypersthene}}{3(Mg,Fe)SiO_3} + H_2O$$

It will be noted that availability of water is an essential condition for this reaction to be displaced to the left and it is considered that a change in the availability of water may alone suffice to convert a lower granulite facies assemblage to an upper amphibolite facies assemblage with no concomitant change in pressure and temperature conditions (Fyfe et al., 1958).

It may be, therefore, that the pressure and temperature conditions prevailing during the metamorphism and migmatitization of these rocks lay in the field of overlap which is believed to exist (Fyfe et al., 1958) between the lower granulite and the upper amphibolite facies. The occurrence of hypersthene especially in the dark blocks included in the migmatite and of a lower granulite facies assemblage in the broad dyke-like band suggests that the blocks and the band were relatively impervious to penetration by the aqueous fluid which, it will be later postulated, was the agent effecting the migmatitization.

LEUCOGRANITIC GNEISS.

Occasionally the dark components of the Banded Migmatite become sparse or die out completely and it passes into a weakly foliated pink rock which is designated the Leucogranitic Gneiss. The most extensive development of this rock is on the coast east of Gaoles where a band some 500' broad runs from Rudha Dubh to Port Ban. This gneiss is generally fine-grained but contains coarser pegmatitic bands concordant with its trend which pass gradually into the finer grained material enclosing them. Although basic bands and lenses are typically absent in this gneiss, it contains blocks and bands of quartzite, calc-silicate rock and marble which are described later (q.v., pp. 196-204). Some similar gneiss occurs associated with the marbles and calc-silicate rocks at Balephetrish.

The Leucogranitic Gneiss has a xenoblastic granular texture with grain size 0.5 to 1.5 mm. It is made up of quartz, microcline and plagioclase with traces of ore, chlorite, zircon and epidote. Table 12 illustrates the modal composition of two examples of this rock.

The quartz forms irregularly outlined, somewhat lobate grains which show strained extinction, are crossed by trains of tiny bubbles and contain occasional small inclusions of microcline.

The microcline forms fresh xenoblastic laths which display well developed cross-hatched twinning and often contain groups of sub-parallel ribbons of albite which are broadest at the grain margins and taper off towards the centres.

	T-29-b	L-6-b
Plagioclase	33.1	28.9
K-felspar	37.0	49.2
Quartz	28.6	21.4
Biotite	-	tr.
Ore	0.3	0.5
Zircon	-	tr.
Serpentine & Chlorite	0.8	tr.
Epidote	0.1	-
Muscovite	tr.	-

Table 12: Modal analyses of Leucogranitic Gneiss.

Location of specimens:
T-29-b: At Rudha Dubh.
L-6-b : Adjacent to the band of metasedements at Sgeir Ghobhlach.

The plagioclase is an albite with a composition An_{12}; it forms xenoblastic, generally heavily sericitized grains in which albite twinning can sometimes be discerned. When a sericitized plagioclase grain abuts against microcline it often has a narrow sericite-free rim, optically continuous with the sericitized portion. Clear rims around sericitized plagioclase grains associated with potash felspar in gneisses have been observed by Sutton and Watson (1950), Eckelmann and Poldervaart (1957), and Harris (1959), all of whom consider them to be in some way connected with the replacement of plagioclase by microcline although the actual process involved is not understood.

The chlorite occurs as small slender laths, presumably pseudomorphing biotite, with which occasional flecks of muscovite are intergrown. There are rare tiny grains of ore, epidote and zircon.

Because of the lack of mafic minerals it is not possible to assign this rock to any definite metamorphic facies.

PETROGENESIS OF THE MIGMATITES.

(I) BANDED MIGMATITES.

Introduction: The general parallelism between the banding of the migmatite and s-surfaces (believed to be traces of original sedimentary banding) in the metasediments suggests that here, as in many areas of deep-seated metamorphism (Read, 1957), the banding is a metamorphic expression of stratification of original sedimentary rocks or the layering of concordant igneous rocks. Isoclinal folding in some of the included basic lenses (Plate 4), which is truncated against enclosing acid material, indicates that folding took place prior to migmatitisation.

The alternation of leucocratic and mafic bands now observed, whether it was generated *de novo* during migmatitisation or whether it is an accentuation of previous sedimentary or igneous banding, probably owes its present condition to one or other of two processes or to a combination of them. The two processes are, firstly, the introduction of quartzo-felspathic material into the rock mass along s-surfaces and secondly, partial segregation of the acid and mafic components of an initially more homogeneous rock. These processes are discussed separately below.

Addition of Extraneous Acid Material: The nature of the mechanism by which this sort of process could have taken place has been much debated. "Emanations, mineralizers, ichors, juices, migmas, magmas ....." (Read, 1957) have all been suggested as the agents which could have effected such a process and terms such as "injection, soaking and imbibition" Walton (1960) have been used to describe the nature of the process. However, the three possible mechanisms appear to be (a) lit-par-lit injection of an acid magma, (b) introduction of material by 'dry' ionic diffusion and (c) introduction of material by diffusion in an aqueous medium.

The first of these mechanisms does not appear to have played an important part in the genesis of the Banded Migmatite. The increase in volume involved in the addition, in magmatic form, of the material which now constitutes the acid bands would have been large, at some localities amounting to some fifty per cent of the rock; such an increase in volume would have been likely to disrupt the simple parallel relationships observed between the banding of the migmatite and that of the associated metasediments. Again, only in very occasional cases is a sharp boundary observed between acid and basic layers in the migmatite, whereas one would expect sharp 'igneous' contacts to be commonly developed if an acid magma had been injected.

The second possible mechanism is the introduction of acid material by ionic diffusion. The hypothesis that migmatitic and granitic rocks may be generated from metamorphic rocks of diverse origin as a result of the introduction into them, by 'dry' diffusion, of elements such as K, Na, Si and O, with the concomitant expulsion of other elements, especially Fe and Mg, has Ramberg as its most notable current advocate. Ramberg (1952) considers that the chemical potentials of elements especially abundant in granitic rocks increase more with increase in temperature and stress than do the potentials of elements less typical of these rocks. He therefore believes that granitizing elements will migrate upwards from deep-seated regions and cause the genesis of granitic rocks at higher levels in the crust. However, Walton (1960) has shown that the rate at which such 'dry' diffusion would be likely to proceed is excessively slow, only a few metres in a million years, and he considers that 'dry' diffusion is unlikely to be a mechanism responsible for the large scale introduction of granitic material in orogenic belts. 'Dry' diffusion is therefore discounted as an important factor in the petrogenesis of the Banded Migmatite.

The third possible mechanism is the introduction of acid material by diffusion in an aqueous medium. Participation of an aqueous fluid in migmatitisation, as a medium of diffusion for migrating elements, has been postulated by several workers including Read (1957), Harris (1959) and Eckelmann and Poldervaart (1957). Walton (1960) has stated that, from the data available, the rate of diffusion in a fluid medium appears to be adequate to account for the genesis of granites and migmatites. In the present case mineral assemblages within the Banded Migmatite are indicative of crystallization in the upper amphibolite facies. However, in the 'resister' bands the assemblages are often indicative of lower granulite facies, while assemblages transitional between the granulite and amphibolite facies are found in the marginal zones of these bands. As has been previously noted, it is considered (Fyfe <u>et al.</u>, 1958) that, under the same conditions of temperature and pressure, assemblages typical of either the lower granulite or the upper amphibolite facies may be generated in a rock depending upon whether the metamorphism is 'dry', which favours the former, or 'wet', which favours the latter. Therefore the postulate that an aqueous fluid was present during migmatitization, but did not extensively penetrate the 'resister' bands, would explain the apparent differences in metamorphic grade; according to this hypothesis the metamorphism and migmatitization may be regarded as essentially one event. Since the diffusion of heat is a faster process than the diffusion of ions and molecules (Bowen, 1948) it is possible that some bands of rock would first recrystallize under 'dry' conditions and later be penetrated by the aqueous fluid; this would explain the occasional local occurrence of retrograde assemblages such as those observed in the marginal zones of the ultrabasic bands of Kilkenneth and Ceann a Mhara.

The hypothesis that the apparent differences in metamorphic grade between the assemblages of the 'resister' bands and those of the Banded Migmatite are largely an expression of the differences in the water vapour pressure prevailing during metamorphism is supported by the work of Yoder and others on the role of water in metamorphism. Yoder (1952) studied the system $MgO-Al_2O_3-SiO_2-H_2O$ and found that, around 600°C and 15,000 p.s.i., it is possible, according to the availability of water, "to have assemblages suggestive of every one of the now-accepted metamorphic facies in stable equilibrium"; and he claimed that "the presence of an 'excess' or 'deficiency' of water vapor greatly influences the mineralogy of a metamorphic rock". Turner (in Fyfe et al., 1958) has criticized Yoder's conclusions as being too sweeping an extrapolation of the somewhat scanty experimental data available but agrees that water vapour pressure is an important factor in metamorphism. According to Turner, variations in water vapour pressure at constant temperature and pressure may determine within which, of two adjacent facies, crystallisation of a rock of given composition will take place. In their recent work on hyperites from southern Norway, Reynolds and Frederickson (1962) have also emphasised the important influence of water on the mineral assemblages produced during metamorphism. After a detailed mineralogical examination of these rocks they concluded that "..... the variables that controlled facies development were not only pressure and temperature, but also the amount of the pervading solution and the composition of it and the invaded rock."

Local variations in the degree of plasticity of the rock during migmatitization is indicated by the occurrence of patches of agmatitic breccia within the generally well banded mass. Since the plasticity of a rock increases with increase in water vapour pressure within it (Kranck, 1954), the presence of these agmatitic patches suggests that the aqueous fluid became concentrated especially at certain loci during the migmatitisation process and caused the banding to break down. The frequent mantling and penetration of bands and lenses of 'resister' rock by coarse acid material may indicate that the migmatitising fluid accumulated against the relatively impervious barriers created by these bands. The acid material often ramifies through cracks and joints in the 'resisters' and therefore must have been in a much more plastic condition than these rocks during migmatitization.

The presence of a fluid phase has already been postulated as an essential prerequisite for the growth of the large albite porphyroblasts in the soda-rich basic gneiss in the Banded Migmatite at Creagan Mora.

Segregation of Acid and Mafic Components: The partial segregation of the acid and mafic components of an initially more homogeneous rock is the second process suggested above as having perhaps contributed to the petrogenesis of the Banded Migmatite. The possible mechanisms which may have effected this process are (a) partial melting and the accumulation of the less refractory portions of the original rock in certain layers, (b) 'dry' ionic diffusion, and (c) diffusion in an aqueous solution.

The first of these mechanisms is believed by some workers (Eskola, 1932) to be responsible for the generation of granitic magmas in regions of deep-seated metamorphism. At a maximum content of water and other volatiles a granitic melt may form around 550° to 600° (Ramberg, 1952; Tuttle and Wyllie, 1957), temperatures which lie within the range believed necessary to promote granulite facies metamorphism. However, it is likely that metamorphic rocks would lose most of the water and other volatiles initially contained in them before such temperatures were attained. Ramberg (1952) therefore considers the production of significant amounts of granitic melt in metamorphic terrancs improbable. Accordingly, it is not believed that partial melting was a major factor in the petrogenesis of the Banded Migmatite, although it may have taken place locally.

Segregation by 'dry' diffusion may also have played some part in the genesis of the migmatite. However, the occurrence of zoned plagioclase grains is evidence against its having been an important factor, for homogeneous mineral grains would be expected to result from diffusion in the solid state. (Walton, 1960).

Segregation by diffusion in an aqueous fluid is the third possible mechanism of segregation mentioned above. This process may have taken place but it is not possible to distinguish the results of it from the effects of the introduction of extraneous material by diffusion in such a medium, as discussed above. In fact the two processes could have proceeded simultaneously, with material which originated within the rock mass migrating in the fluid phase along with introduced material.

<u>Conclusions</u>: The available evidence suggests therefore, that the migmatitization process was promoted by the presence of an aqueous fluid within which migration of material took place while the high temperatures which caused the granulite facies metamorphism of the 'resister' bands were maintained. It is considered that this migration of material, which would be likely to take place most readily along privileged paths (Read, 1957) such as the traces of bedding planes, caused the generation of the banding now observed.

The metasedimentary rocks preserved within the Banded Migmatite mass are principally marbles, calc-silicate rocks and granulites. The sedimentary types from which these metamorphites originated would be expected to be accompanied in a geosynclinal series by large amounts of greywackes and shales. Therefore it seems reasonable to postulate that some at least of the Banded Migmatite mass originated from such sediments. The mean composition of the four analysed specimens of Banded Migmatite is compared with an

	A	B
SiO_2	64.5	64.7
TiO_2	0.4	0.5
Al_2O_3	16.0	14.8
Fe_2O_3	1.9	1.5
FeO	3.1	2.9
MnO	0.1	0.1
MgO	2.1	2.2
CaO	4.8	3.1
Na_2O	4.4	3.1
K_2O	2.6	1.9
P_2O_5	0.1	0.2
H_2O+	0.5	2.4
H_2O-	-	0.7
SO_3	-	0.4
CO_2	0.2	1.3
S	-	0.2
	100.7	101.0

Table 13: A comparison of the chemical composition of the Banded Migmatite with that of greywackes.

A. Mean composition of the four analyses of Banded Migmatite included in Table 2.

B. Mean composition of 23 greywackes (Pettijohn, 1956).

average composition of greywackes in Table 13. It will be observed that the two compositions are similar although the migmatites are somewhat richer in lime, alkalies and alumina than the greywackes and, as would be expected, poorer in water and carbon dioxide. Four analyses are slight evidence on which to base any hypothesis regarding the origin of a large and variable rock mass; however, this comparison does demonstrate that the sort of mineral assemblages found within the Banded Migmatite could be produced by the metamorphism of sedimentary rocks of the greywacke type without the addition of large amounts of extraneous material. The water constituting the fluid phase, which it is postulated promoted migmatitization, could be part of the water contained in the original sedimentary rock.

It can be argued that the term 'migmatite' should not be applied to a rock which has formed by the action of an aqueous fluid, since the term as used originally by Sederholm implied the participation of a granitic magma in the petrogenesis of rocks to which it was applied. Modern workers, however, employ the term in cases where the existence of a magmatic phase during migmatitization is not postulated (Eckelmann and Poldervaart, 1957; Wahlstrom and Kim, 1959; and Ward, 1959). Neither is the influx of extraneous material deemed an essential condition for the use of the term; Belliere has said "les roches migmatitiques pourraient engendrées, au moins dans certain cas, par un processus de mobilisation de certaines parties de la roche trame originelle, ces parties, après un court transport, étant fixées a nouveau dans le sub-strat lui-même" (Belliere, 1960). Migmatitization of this sort in which little or no foreign material is added to the rock mass has been termed endomigmatitisation (Belliere, 1960) and contrasts with exomigmatitisation in which introduction of certain elements and the concomitant expulsion of others is an essential part of the process.

Since the composition of the original rocks from which the Banded Migmatite was engendered is not known, the nature of the migmatitisation process cannot be ascertained. However, the comparison made in Table 13 suggests that it may have been essentially endomigmatitic.

(II) MASSIVE MIGMATITE.

In this rock, into which the Banded Migmatite grades on the south side of Ben Hynish, the mineral assemblage is generally indicative of the hornblende granulite subfacies of the granulite facies but occasional bands with sillimanite-almandine subfacies assemblages, similar to that in the Banded Migmatite, are found within it.

It seems likely, considering the intimate field relationship between the Banded Migmatite and the Massive Migmatite, that they must have been subjected to approximately the same conditions of temperature and pressure during metamorphism and that the differences in their mineralogy are the expression of a relative lack of water within the latter rock during metamorphism. This lack of water may have been due to a low water content in the original rocks which recrystallized to form the Massive Migmatite or may indicate that they were less permeable than were the rocks now represented by the Banded Migmatite and therefore less thoroughly soaked by the aqueous fluid which is postulated as the agent effecting the migmatitisation.

Examination of this rock has not revealed any clues as to its ultimate origin; however, since it grades into Banded Migmatite, it may also represent highly altered sedimentary material.

(III) CONTORTED MIGMATITE.

This phase is distinguished from the Banded Migmatite by its streaky rather than banded appearance and by the widespread occurrence within it of contortions and crenulations. This sort of apparently irregular deformation has been described as wildfolding by Kranck (1953) who considers that it is probably impressed on migmatites at a time when they are in an extremely plastic condition due to a relatively high concentration of water within them. This suggests that the rocks now represented by the Contorted Migmatite either had a higher initial water content, or were more easily penetrated by the migmatitizing fluids, than those which were transformed into the Banded Migmatite.

No positive evidence as to the ultimate origin of the Contorted Migmatite has been observed; but, since it is postulated that the original rock either had a high initial water content or was highly amenable to penetration by migmatitising fluids, a sedimentary origin seems more probable than an igneous one.

(IV) LEUCOGRANITIC GNEISS.

The gradational contacts between this rock and the Banded Migmatite suggest that it also attained its present condition as a result of penetration by the postulated migmatitizing fluid. The almost complete lack of mafic minerals within it indicates that either the original rock which recrystallized to give rise to the Leucogranitic Gneiss was lacking in mafic material, or that the elements necessary to effect granitization became locally concentrated in the fluid phase and that there was concomitant expulsion of elements, especially Fe and Mg, necessary for the production of mafic minerals.

PART III

INTERMEDIATE, BASIC AND ULTRABASIC GNEISSES

INTERMEDIATE, BASIC AND ULTRABASIC GNEISSES.

(I) BEN HOUGH INTERMEDIATE GNEISS.

1) Field Observations.

Ben Hough is a north-south trending ridge of high ground, about a mile long and a quarter of a mile wide, the highest point of which has an elevation of 368 feet. It is made up of a fairly homogeneous mass of fine to occasionally medium grained, weakly foliated, medium grey, gneiss of intermediate composition which has mineralogical affinities with the intermediate members of the charnockitic series.

The presence of bands of shattered rock and veins of flinty crush near the base of the steep slope which marks the southern extremity of this body suggests that it has there a tectonic contact with the adjacent Banded Migmatite. Elsewhere the boundaries of the body are not exposed; but its direction of elongation, and also the trend of the weak foliation within it, are approximately parallel to the trend of the banding in the nearby migmatite.

2) Texture and Mineralogy.

The texture of this gneiss is xenoblastic granular with grain sizes generally ranging from 0.25 to 1.5 mm., but with occasional laths of felspar up to 3.0 mm. in length. There is a slight tendency for the mafic grains to be aggregated in clusters but this is never a well marked textural feature. The accompanying table of modal analyses (Table 14) shows the mineralogical

	H-32-b	H-35-a	H-38
Plagioclase	69.0	70.4	75.8
Potash Felspar	8.0	7.2	4.0
Clinopyroxene	3.3	4.6	3.7
Orthopyroxene	8.2	10.9	8.4
Hornblende	8.0	4.2	4.5
Biotite	0.3	0.2	0.1
Apatite	0.6	0.5	0.3
Ore	2.4	2.2	3.2
Quartz	0.2	-	-

Table 14: Modal analyses of examples of the Ben Hough intermediate gneiss.

Location of specimens:
H-32-b: 440 yds. N.N.E. of the summit of Ben Hough.
H-35-a: At the summit.
H-38 : 580 yds. S.S.W. of the summit.

	H-38	H-35-a	A
SiO_2	54.90	55.6	56.8
Al_2O_3	19.47	18.3	16.7
Fe_2O_3	2.92	3.4	3.2
FeO	4.85	6.7	4.4
MgO	3.80	3.5	4.2
CaO	6.73	6.9	6.7
Na_2O	5.25	5.3	3.4
K_2O	1.55	1.2	2.1
H_2O+	0.49	-	1.4
TiO_2	0.63	-	0.8
MnO	0.12	-	0.1
P_2O_5	0.13	-	0.2
	100.84	100.9	100.0

Table 15: Chemical composition of the Ben Hough intermediate gneiss.

H-38 : Analysed specimen. (Analyst: I.G.L. Sinclair)

H-35-a: Chemical composition calculated from modal analysis.

A : Average composition of 70 diorites (Tyrell, 1929).

composition of specimens of the gneiss taken at intervals of about a quarter of a mile along the ridge and illustrates its homogeneous nature. Chemical compositions of two of the specimens are given in Table 15 and features of individual constituent minerals are described below.

Orthopyroxene: The orthopyroxene forms xenoblastic laths which are often intergrown with clinopyroxene and hornblende and sometimes contain small inclusions of the latter mineral as well as some ore grains. It is rather weakly pleochroic (X and Y - very pale pink, Z - very pale green) and shows some patches of dark brown staining. Minor alteration to bastite has commonly taken place along the irregular cracks which traverse the grains, and there is some alteration to biotite around their margins. Inclined extinction and zoning are commonly observed and some grains contain many fine lamellae parallel to their c-axes which extinguish in two distinct groups, in the manner of albite twins in plagioclase. Plate 15 illustrates this feature of the orthopyroxene.

Lamellae of exsolved clinopyroxene parallel to (100) occur in orthopyroxene of the Bushveld type (Deer et al., 1963) and Parras (1958) has observed the same phenomenon in the orthopyroxenes of certain charnockitic rocks in Finland. However, some workers consider that these lamellae are not due to the exsolution of a clinopyroxene phase in an orthopyroxene host in every case; twinning or translation gliding have been suggested as alternative explanations for some occurrences of this phenomenon (Deer et al., 1963). In the present instance twinning or gliding seems to be the more likely explanation, for no difference in refractive index can be perceived

PLATE 15.

Den Hough intermediate gneiss. Two ortho-pyroxene grains, exhibiting lamellar structure and zoning, can be seen in the centre of the picture. (X 60, crossed nicols) between adjacent lamellae and the pleochroic shades appear to be uniform throughout individual grains.

The optic angle, -2V, of this pyroxene ranges from 54° to 60° and a variation of as much as 5° can sometimes be observed in a single thin section. The refractive index, $N\gamma$, is $> 1.71 < 1.72$ and this together with the optic angle indicates an iron-rich hypersthene.

<u>Clinopyroxene:</u> Clinopyroxene forms fresh, pale green, completely xenoblastic grains which are often embayed by plagioclase and intergrown with orthopyroxene and hornblende. Occasional small inclusions of hornblende and some grains and specks of ore occur within the clinopyroxene grains, and they occasionally show patches of dark brown staining similar to that observed in the orthopyroxene. Its optical properties, +2V 58°, $N\alpha$ 1.683 and $N\gamma$ 1.713 are those of salite (Hess, 1959).

<u>Hornblende:</u> Xenoblastic, embayed grains of hornblende, generally somewhat smaller than those of the pyroxenes, occur singly or in clusters with the pyroxenes and ore. The hornblende grains contain granules and streaks of ore and patches of dark brown staining and occasionally have small flecks of biotite clinging to their margins. The optic angle, -2V, of the hornblende is 72°, and it has the following refractive indices: $N\alpha$ 1.664 and $N\gamma$ 1.683.

<u>Plagioclase:</u> The plagioclase is fresh and forms completely xenoblastic grains which have somewhat strained extinction. Albite twinning is generally present but weakly developed. Occasionally the plagioclase contains groups of tiny anti-perthitic potash felspar inclusions and some myrmekitic

quartz intergrowths in the plagioclase where it abuts against potash felspar. Rare small hornblende grains are the only other inclusions. The plagioclase is an oligoclase with a composition ranging from An_{20} to An_{25}.

Potash Felspar: Potash felspar occurs sporadically forming interstitial xenoblastic grains. It is always fresh, has somewhat irregular extinction, and is free from inclusions except for occasional slender tapering ribbons of albite.

Accessories: Small irregular grains of iron ore occur throughout the rock, often associated with hornblende or pyroxene, and there are occasional small sub-rounded laths of apatite in which groups of dark acicular inclusions arranged parallel to the c-axis of the apatite can be observed.

Comparison with Charnockites: Mineralogically this rock resembles the intermediate charnockites of India (Pichamuthu, 1953), both in the nature of the assemblage and the features of the individual constituents. However, although anti-perthitic, perthitic and myrmekitic intergrowths in the felspars and the aggregation of the mafic constituents into clusters, textural features typical of the Indian rocks, are sometimes observed in this case, they are not strongly developed. Again, whereas, according to Pichamuthu, the typical intermediate charnockites are composite rocks with readily distinguishable basic and acid components, the Ben Hough rock is homogeneous in nature.

3) Metamorphic Facies.

The mineral assemblage noted above is: oligoclase; potash felspar;

orthopyroxene; clinopyroxene; hornblende, with minor amounts of biotite, apatite and ore. This assemblage is indicative of crystallization in the hornblende granulite subfacies. (Fyfe et al., 1958)

The presence of small inclusions of hornblende within grains of both varieties of pyroxene, although pyroxene inclusions do not occur in hornblende grains, suggests that the pyroxenes, at least in part, formed at the expense of pre-existent hornblende during the stepping up of metamorphic grade from almandine amphibolite facies to granulite facies conditions.

Biotite would not be expected to form under granulite facies conditions and its presence in this rock, generally as little flecks around the periphery of pyroxene or hornblende grains, indicates that slight retrograde metamorphism took place when conditions eased after a period of maximum metamorphic intensity.

4) Origin.

The homogeneous nature of this rock, demonstrated by its uniform appearance in the field and the similarity of modal analyses of samples from widely separated outcrops, suggests that it probably originated as an intrusive igneous body which has been recrystallized under lower granulite facies metamorphic conditions.

As will be seen in Table 15, apart from being rather high in alumina and soda and low in water, the composition of the Ben Hough rock is analogous to an average composition of diorites; the original igneous rock is thus likely to have been dioritic in nature.

(II) BALEPHETRISH HILL BASIC GNEISS.

1) Field Observations.

The small hill at Balephetrish is made up of a mass of dark grey, weakly foliated, fine to medium grained basic gneiss. The contacts of this basic gneiss with the surrounding rocks are not exposed but the trend of the foliation within it shows a general concordance with the trend of the banding in the adjacent Banded Migmatite.

The gneiss is occasionally cut by acid pegmatitic veins up to about two or three inches in width. Planes of crushing occur within the gneiss and there is very occasionally some development of narrow stringers of flinty crush.

2) Texture and Mineralogy.

This rock has a xenoblastic granular texture with most grains lying in the 0.5 to 2.0 mm. size range. Hornblende and pyroxene grains generally show some tendency to elongation parallel to the weak foliation of the rock but this is never a prominent textural feature.

The accompanying table of modal analyses (Table 16) illustrates the sort of mineralogical variation encountered within this body of basic gneiss. It will be observed that the amounts of hornblende and of total pyroxene appear to vary antipathetically. Features of the individual constituent minerals are briefly described hereunder.

<u>Hornblende</u>: The hornblende is strongly pleochroic with X - brownish

	D-4	D-7	4	24
Plagioclase	52.0	45.0	50.5	38.7
Hornblende	25.3	28.1	30.6	48.6
Clinopyroxene	15.9	15.6	2.7	4.5
Orthopyroxene	3.2	7.0	13.5	3.8
Ore Minerals	3.4	4.3	2.7	4.4
Apatite	0.2	-	-	tr.
Biotite	-	-	-	tr.

Table 16: Modal analyses of examples of the Balephetrish Hill basic gneiss.

Location of specimens:

D-4: West side of the pathway leading to bulb-packing station, 30 yds. from its junction with the Scarinish road.
D-7: Summit of Balephetrish Hill.
4 : Southern end of the disused quarry on the west side of the hill.
24 : Northern end of the same quarry.

yellow, Y - olive green and Z - medium brownish green. It forms xenoblastic grains which have fairly straight margins when in mutual contact but are generally embayed and have frayed margins when they abut against plagioclase or pyroxene. The hornblende is fresh and free from inclusions except for occasional specks of ore and irregular patches of dark brown staining. Its optic angle, -2V, is 67^{o} and it has the following refractive indices: $N\alpha$ 1.668 and $N\gamma$ 1.686.

Clinopyroxene: The clinopyroxene is a very pale green non-pleochroic variety which forms completely xenoblastic grains and is often intergrown with hornblende and clinopyroxene, the intergrowths in the latter case often being isoaxial. It is generally fresh and contains some small, irregular hornblende inclusions and occasional ore grains. The optical properties, +2V, $N\alpha$ 1.686 and $N\gamma$ 1.708, indicate that this pyroxene lies on the border between the diopside and salite fields. (Hess, 1949)

Orthopyroxene: The orthopyroxene occurs as very irregularly outlined, somewhat skeletal grains which occasionally form porphyroblasts up to 8.0 mm. in length but most often are of the same order of size as the clinopyroxene and hornblende grains, and are intergrown with them. A dense network of irregularly anastomosing cracks, along which some alteration to bastite has taken place, dissects the orthopyroxene grains. Occasional small grains of ore and of hornblende occur as inclusions and when two or three hornblende inclusions occur within a single orthopyroxene grain they are sometimes in optical continuity. Weak pleochroism in shades of pale pink can generally be observed. The optic angle, -2V, = 50^{o} and $N\gamma$ = 1.710, properties which indicate an alumina-bearing, iron-rich hypersthene (Deer et al., 1963)

Plagioclase: The plagioclase forms completely xenoblastic grains which embay into the hornblende and pyroxenes. It is generally fresh and shows weakly developed albite twinning and, occasionally, some normal zoning. It contains small ore grains and some small, frayed hornblende inclusions; and sometimes, when it is embaying into large hornblende grains, it is crossed by a network of pale green chlorite veins. The plagioclase is an oligoclase with an anorthite content varying from 25 to 30 per cent.

Accessories: Small irregularly outlined, but generally equant, grains of ore are common throughout the rock and occasional tiny biotite flakes cling to them. There are very occasional small, sub-rounded apatite laths.

The pegmatitic veins which cut this basic gneiss are made up of coarse grained aggregates of oligoclase and quartz within which occur occasional laths of much altered hypersthene which occasionally have irregular grains of fresh biotite clinging to their margins. There are also occasional small interstitial grains of potash felspar.

3) Metamorphic Facies.

The mineral assemblage within this rock, namely oligoclase; hornblende; clinopyroxene; orthopyroxene, with minor amounts of ore and apatite, is indicative of crystallization in the hornblende granulite subfacies of the granulite facies. This subfacies is considered by Turner (in Fyfe et al., 1958) to represent a transition between the almendine amphibolite facies and the granulite facies. It may be that the antipathetic relation observed between the amount of pyroxene and the amount of hornblende present indicates that equilibrium was not achieved within this body of basic gneiss, and that, in certain portions of it, change from an almandine amphibolite facies assemblage to a granulite facies assemblage has advanced further than in others. There is no textural evidence to suggest that the hornblende formed from pyroxene in response to diaphthoresis.

The occurrence in the pegmatitic veins of much altered hypersthene grains rimmed by biotite laths suggests that partial diaphthoresis took place in those veins after the main period of metamorphism, for biotite is not a possible phase in the hornblende granulite subfacies. The presence of biotite, along with the occurrence of some interstitial potash felspar grains, within these veins suggests that they have been channels along which potash migrated.

4) Origin.

The difficulty in attempting to decide whether amphibolites originated as igneous or sedimentary rocks is well known. Eckelmann and Poldervaart (1957), after a detailed mineralogical and chemical examination of pyroxene-bearing amphibolite bands included in Archaean migmatites of the Beartooth Mountains area of Montana and Wyoming, concluded that the field relationships of the rocks remain the best criterion for distinguishing between para- and ortho-amphibolites, as did Harris (1959) working in the same area. These authors class well foliated and structurally conformable sheets as para-amphibolites and plug-shaped bodies as ortho-amphibolites. In the case of the Balephetrish basic gneiss no distinguishing criteria have been observed and, accordingly, this body may have originated as basic igneous rock, as tuff, or as a basic sedimentary rock such as dolomitic shale.

(III) BALEPHUIL BASIC GNEISS.

1) Field Observations.

At Balephuil there occurs a body of medium-grained, weakly foliated basic gneiss which has a mottled appearance in white and dark greenish grey. Although the margins of this body are not exposed, it appears to be over a quarter of a mile wide and to extend parallel to the trend of the adjacent Banded Migmatite. Scattered outcrops of similar rock also occur on the north-west shoulder of Ben Hynish.

2) Texture and Mineralogy.

This rock is found in thin-section to be made up of oligoclase, hornblende and biotite accompanied by minor amounts of ore. The oligoclase, which constitutes some fifty per cent of the volume of the rock, forms xenoblastic laths up to about 6.0 mm. in length which generally show albite and sometimes some pericline twinning and are often partly, and sometimes completely, sericitized. Hornblende forms xenoblastic to occasionally subidioblastic grains, mostly about 2.0 - 3.0 mm. in size, which make up some forty per cent of the volume of the rock. It is a variety pleochroic from pale to medium olive green and is generally fresh and free from inclusions apart from occasional granules of ore. Biotite occurs in minor amounts as narrow laths up to 2.0 mm. in length which often dissect hornblende grains. The biotite is strongly pleochroic with X - pale brown, Y and Z - medium reddish brown; it is generally fresh but sometimes partially replaced along cleavages by narrow strips of sillimanite and occasionally of epidote. Small irregular grains of ore are fairly common throughout this rock.

3) <u>Metamorphic Facies.</u>

The assemblage in this basic gneiss is indicative of the sillimanite-almandine subfacies of the almandine amphibolite facies; the assemblages in the basic gneiss of Balephetrish Hill and in the basic bands within the Banded Migmatite, however, are suggestive of the lower subfacies of the granulite facies. Since no pyroxene remnants have been observed within the hornblende grains in this Balephuil rock, there is no reason to suppose that the assemblage within it has resulted from the diaphthoresis of a granulite facies assemblage. The mineralogical differences between it and the other basic rocks are probably due to water being more freely available within this Balephuil rock during metamorphism than in the others.

The difficulty in distinguishing between ortho- and para-amphibolites was commented upon above; no conclusive evidence as to the origin of the basic gneiss at Balephuil has been observed.

(IV) <u>ULTRABASIC GNEISS OF KILKENNETH AND CEANN A MHARA.</u>

1) <u>Field Observations.</u>

On the west coast of Tiree there occur two bands of ultrabasic rock some twenty to thirty feet wide enclosed by the Banded Migmatite and elongated parallel to the banding within it. A band of very similar rock 600 feet wide occurs on the east coast of the peninsula of Ceann a Mhara, again conformable with the adjacent Banded Migmatite. The two bands on the west coast are located at Rudha Hanais and Eilean Ghreasamuill.

Mineralogically the ultrabasic gneiss is similar at different localities but each occurrence has certain distinct field characteristics which are briefly noted below.

i) <u>Rudha Hanais:</u> At this locality a very massive ultrabasic band some thirty feet wide is adjacent, on its eastern margins, to some metasedimentary rocks, including marble, but on its western margin it abuts against Banded Migmatite. The ultrabasic rock is dark greenish grey and is studded by small brown spots which mark the loci of orthopyroxene grains. It is weakly foliated and is free from acid veining.

ii) <u>Eilean Ghreasamuill:</u> The tidal island of Eilean Ghreasamuill is made up of a mass of fairly well foliated light to medium grey basic gneiss, in the centre of which occurs an ultrabasic band some twenty feet wide. The ultrabasic rock is again massive and is not penetrated by acid veins. The basic gneiss enclosing this ultrabasic band is a foliated plagioclase hornblende rock, in which there occur minor amounts of clinopyroxene and orthopyroxene.

iii) <u>Ceann a Mhara:</u> The east side of this peninsula is made up of a band of ultrabasic rock some six hundred feet wide. The western margin of this band is in contact with Banded Migmatite, against which it has an abrupt but concordant junction, while on the east it is bounded by the sea except at the west end of Traig a Bheidhe. Here it is in contact with several feet of calc-silicate rock which, in turn, is in contact with foliated hornblende- and plagioclase-bearing rock containing minor amounts of clinopyroxene and orthopyroxene.

The ultrabasic rock at Ceann a Mhara has often a mottled appearance due to the occurrence of clusters of dark greenish-grey hornblende grains up to 10.0 mm. in diameter set in a fine grained light greenish-grey matrix. These clusters of hornblende grains become occasionally somewhat elongated and the rock has then a streaky rather than a mottled appearance. Sometimes, too, the spotted rock grades into a relatively homogeneous, fine-grained phase by a gradual reduction in the size of the hornblende clusters and their occasional complete disappearance.

2) Texture and Mineralogy.

These ultrabasic gneisses have a xenoblastic, somewhat inequigranular, texture with grain sizes ranging from 0.25 to 4.0 mm. The largest grains are most often of hornblende but sometimes of clinopyroxene. In the centres of the bands the mineral assemblage is hornblende, which constitutes about two thirds of the volume of the rock, orthopyroxene, clinopyroxene and minor ore with occasionally some plagioclase and traces of biotite. Near the margins of the bands however, the amount of orthopyroxene is greatly reduced, and that which is present is largely altered to bastite; the amount of diopside present, however, is increased and plagioclase may constitute up to ten per cent of the rock. The hornblende in the marginal zones is sometimes partially replaced by pale amphibole which, itself, is sometimes partially replaced by calcite. Examples of both the central and marginal assemblages are given in the accompanying table of modal analyses (Table 17) and the inequigranular texture of an example from the centre of one of the bands is illustrated in Plate 16.

Features of the individual constituent minerals are described below.

Hornblende: The dominant mineral of these ultrabasic rocks is hornblende. It is strongly pleochroic from straw to medium brownish green and forms grains up to about 4.0 mm. in size which are often sub-idioblastic when in mutual contact but are generally embayed when they abut against pyroxene. The hornblende is free from inclusions except for occasional streaks of ore. It is quite fresh in the central portions of the bands but in the marginal portions it is partly altered to a very pale green amphibole. The replacement of the hornblende by pale amphibole generally commences around the margins of hornblende grains and the two minerals often form isoaxial intergrowths. Finely granular calcite is often associated and intergrown with the pale amphibole. The hornblende has -2V 82° and $N\alpha$ 1.654, $N\gamma$ 1.672.

Orthopyroxene: The orthopyroxene is pleochroic with X - pale pink, Y and Z pale green. It forms completely xenoblastic grains which embay into and often contain small inclusions of hornblende and occasional ore

	H-9-h	H-9-i
Hornblende	64.5	69.7
Colourless Amphibole	-	1.6
Clinopyroxene	9.3	15.1
Orthopyroxene	24.3	1.1
Plagioclase	-	10.4
Biotite	-	0.6
Apatite	-	0.2
Ore Minerals	1.9	0.4
Calcite	-	0.1
Serpentine	-	0.8

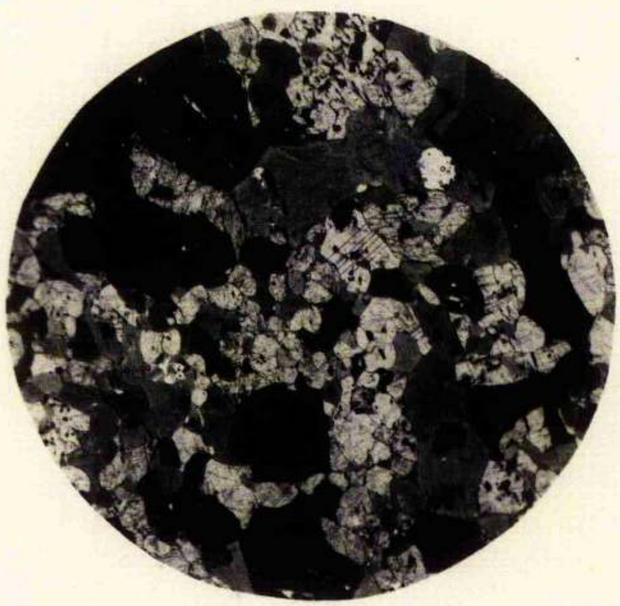
Table 17: Modal analyses of examples of the ultrabasic band at Rudha Hanais.

Location of specimens:

H-9-h: At the centre of the band.

H-9-i: Two feet from the east margin.

PLATE 16.



Inequigranular texture in the centre of the band of ultrabasic gneiss at Rudha Hanais. The dark grains are hornblende and the light coloured ones orthopyroxene and clinopyroxene. (X 25) grains. In the central portions of the bands the orthopyroxene is only very slightly altered, along cracks and peripherally, to serpentinous material; but in the marginal zones, where it occurs in much smaller amounts, it is sometimes completely replaced by bastite. The optical properties of the orthopyroxene, -2V, 59° to 65°, $N\gamma$ 1.704, indicate an intermediate hypersthene (Hess, 1949).

Clinopyroxene: The clinopyroxene is pale green and non-pleochroic. It forms irregularly outlined, xenoblastic grains which contain many grains and streaks of ore and occasional small hornblende inclusions. In the marginal zones the clinopyroxene sometimes appears to be partially replaced by hornblende, small flecks of which first appear along cleavages and from there spread out over the pyroxene grains. The optical properties of the clinopyroxene, +2V 55°, $N\alpha$ 1.673 and $N\gamma$ 1.702, indicate that it is a diopside (Hess, 1949).

Plagioclase: In the central portions of these ultrabasic bands plagioclase is most often absent but it may make up some ten per cent of the volume of the marginal zones. It forms fresh, xenoblastic grains which embay into and occasionally contain irregular fragments of hornblende and pyroxene. The plagioclase, which is an andesine with a composition of An_{40}, often displays some very fine albite twinning and some normal zoning; occasionally groups of mutually parallel tiny dark rods occur within it.

Scapolite: Scapolite occurs occasionally in the marginal assemblages as xenoblastic laths up to 1.5 mm. in length which are often clouded by a very fine black dust and contain tiny dark rods orientated parallel to the c-axes, similar to those observed in the plagioclase grains. Its refractive indices, N_e 1.561 and N_o 1.593, indicate that it is a mizzonite with a composition of $Ma_{25}Me_{75}$.

<u>Biotite</u>: Minor amounts of biotite occur in the marginal zones and occasionally in the centres of the bands. The biotite forms small flecks around the margins, and sometimes along the cleavages, of hornblende grains.

<u>Apatite</u>: Apatite is confined to the marginal assemblages where it occurs as occasional small, sub-rounded laths which contain groups of parallel dark rods similar to those observed in the scapolite and plagioclase.

3) <u>Metamorphic Facies</u>.

The mineral assemblage in the centres of these ultrabasic bands, namely, hornblende, diopside and hypersthene, is symptomatic of crystallization in the hornblende granulite subfacies of the granulite facies (Fyfe <u>et al</u>., 1958). These minerals are also present in the marginal zones but there the amount of hypersthene is greatly reduced and that of diopside somewhat increased; in the marginal zones the hypersthene and diopside appear to be unstable for the former is largely replaced by serpentine and the latter partly replaced by hornblende. Plagioclase, scapolite, biotite and apatite are present in the marginal zones but generally absent in the centres.

The marginal zones thus may have resulted from partial diaphthoresis of the central, high grade assemblages at a time when there was some metasomatic introduction of silica, alumina, soda, potash and the volatiles necessary for the generation of scapolite.

	1	2
SiO_2	46.05	45.6
Al_2O_3	10.57	8.3
Fe_2O_3	2.96	2.3
FeO	10.77	10.3
MgO	18.17	21.7
CaO	8.72	7.5
Na_2O	1.00	1.3
K_2O	0.52	0.4
H_2O	0.53	0.6
TiO_2	1.39	1.7
MnO	0.27	0.3
P_2O_5	0.02	0.1
	100.97	100.1

Table 18: Comparison of the chemical composition of the ultrabasic gneiss at Rudha Hanais with a mean composition of ultrabasic lavas.

1. Analysis of specimen H-9-h from the centre of the ultrabasic band at Rudha Hanais. (Analyst: I.G.L. Sinclair)

2. Mean of ten analyses of oceanite (ultrabasic olivine-rich basalt) (Tyrell, 1929).

4) Origin.

Positive evidence as to the origin of these ultrabasic rocks is lacking, but the occurrence of regularly distributed clusters of coarse hornblende grains in a fine-grained matrix, observed in some portions of the broad ultrabasic band at Ceann a Mhara, may be a metamorphic expression of an original porphyritic igneous texture.

In Table 18 a chemical analysis of a specimen from the centre of the ultrabasic band at Rudha Dubh is compared with an average composition of ultrabasic lavas and the two are seen to be similar. It seems reasonable to postulate, therefore, that these rocks may have originated as ultrabasic igneous rocks which occurred either as lavas or as intruded sheets.

PART IV

METASEDIMENTS

METASEDIMENTS.

INTRODUCTION.

Although an ultimate sedimentary origin is postulated for some at least of the mass of migmatites which make up the greater part of the Lewisian complex of Tiree, the term metasediment is reserved for those modifications such as marble, calc-silicate rock, quartzite and granulite, which have proved resistant to the changes wrought on the surrounding rocks by the migmatitization process and of which the sedimentary origin is virtually certain and not merely a hypothesis.

Lenses and bands of metasediments occur at many localities within the Banded Migmatite and they are generally elongated parallel to the banding of that rock; any compositional banding observed within them is also parallel to that direction in most cases. Descriptions of the principal occurrences of metasediments are given below. In addition to these occurrences occasional isolated lenses of marble and calc-silicate rock occur within the Banded Migmatite.

(I) DUN GOTT.

The largest mass of metasediments exposed lies at Dun Gott, where a belt some two hundred feet wide runs along the north-west trending shoreline from the steamer pier to the beginning of the Traigh Mhor beach, a distance of about half a mile. These rocks, which generally dip steeply to the south-west and strike in a direction approximately parallel to the direction of the shore line, are bounded on the south-west by Banded Migmatite with a similar trend, while on the north-east side they pass into the sea.

Within this mass of metasediments a considerable variety of rock types is found. The bands of calc-silicate rock and marble are often extremely contorted and have irregular weathering surfaces, whereas the bands of granulite and schist have a somewhat massive appearance. Marble, as well as occurring as distinct bands, often forms lenses a few feet long within the granulite and calc-silicate bands. These lenses have likely originated by the squeezing out of marble which under conditions of stress is more plastic than other rocks. The occurrence of lenses of marble in highly metamorphosed Lewisian rocks has been recorded from South Harris by Davidson (1943) and from Glen Dessary by Harry (1951) both of whom ascribe this mode of occurrence of the marble to its plastic behaviour under stress.

For descriptive purposes the Dun Gott metasediments can be divided into the types listed below but in the field gradational contacts between the different types often exist and make the mapping of individual bands difficult. However, a sketch map of this occurrence of metasediments is included. (Figure 10)

(a) Granulites

(b) Marbles

(c) Calc-silicate rocks

(d) Quartzites

(e) Graphite-rich rocks

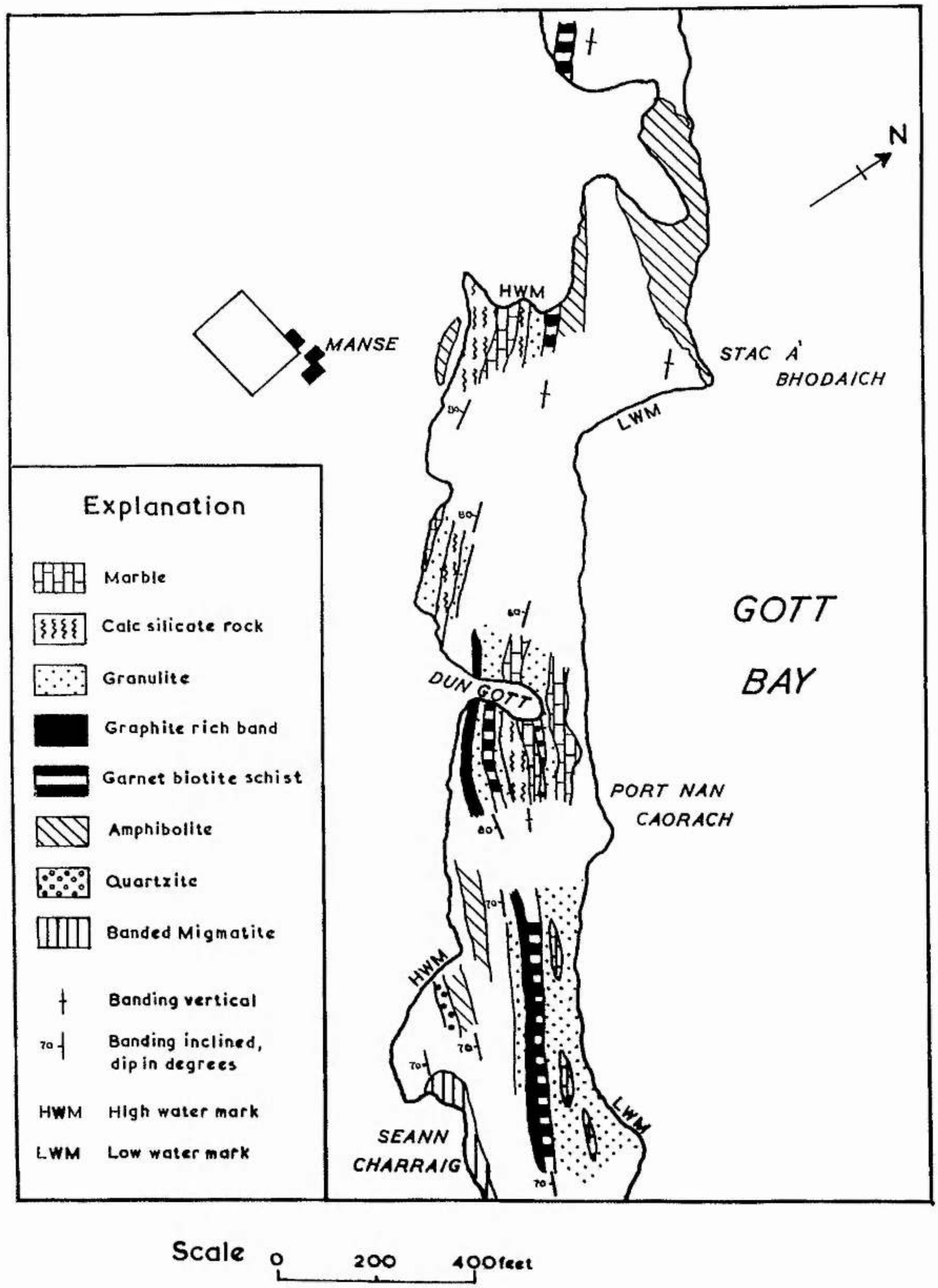


Figure 10: Sketch-map of the metasediments at Dun Gott.

(f) Amphibolite

(g) Garnetiferous Biotite Schist

These various rock types are now described individually:

(a) Granulites.

These are light to medium grey, fine grained, often quite massive rocks in which compositional banding can often be observed. Occasionally, when they contain significant amounts of mica, they are slightly schistose.

In section they are seen to have a xenoblastic granular texture with most grains lying in the 0.25 to 1.0 mm. size range but coarse quartzo-felspathic bands with grains up to 3.0 or 4.0 mm. in diameter do occur occasionally. The banding observed in hand-specimen is seen to be generally due to variations in mineral content, alternations of plagioclase-rich and scapolite-rich bands being a common example of this, but some banding due to variations in grain size also occurs. Individual bands vary from one to ten millimetres in thickness. Plate 17 illustrates the granular texture of an example of the Dun Gott granulites.

Plagioclase is always present and is generally the dominant constituent of these granulites. The other constituents, which occur in greatly varying proportions are potash felspar, quartz, diopside, amphibole, phlogopite, scapolite, sphene, and ore minerals along with accessory amounts of apatite, serpentine, chlorite and calcite. The accompanying table of modal analyses (Table 19) illustrates the variation in the relative porportions of the constituent minerals present in various specimens of these granulites.

PLATE 17.

Texture of a granulite band at Dun Gott. Composed principally of plagioclase and potash felspar with minor amounts of diopside, sphene, phlogopite and ore. (X 15 crossed nicols)

Location of specimens featured in Table 19.

D-1-b: 850' E.10°S. of the manse at Dun Gott.
D-1-c: Same locality as D-1-b.
D-16-f: 520' N.25°E. of the manse.
D-17-c: 410' N.25°E. of the manse.
D-20-b: 650' W. of the manse.
D-20-d: Same locality as D-20-b.
D-21-c: 700' E.10°S. of the manse.
D-21-e: Same locality as D-21-c.
D-22-d: Foreshore, 440' N.30°W. of Seann Charraig.
D-22-e: Same locality as D-22-d.
D-22-f: 220' N. of Seann Charraig.
D-27-a: 330' N.30°E. of Seann Charraig.

	D-1-b	D-1-c	D-16-f	D-17-c	D-20-b	D-20-d	D-21-c	D-21-e	D-22-d	D-22-e	D-22-f	D-27-a	Range
Plagioclase	59.0	37.8	67.3	47.2	53.5	32.6	78.7	65.4	63.7	79.6	60.0	39.6	32.6 - 79.6
K-Felspar	tr.	-	0.2	-	3.1	27.5	-	8.9	13.4	0.7	-	28.1	0.0 - 28.1
Quartz	2.1	-	-	-	26.1	-	0.3	22.7	0.4	0.1	-	7.0	0.0 - 26.1
Diopside	30.5	29.4	11.0	21.2	1.2	27.1	4.3	2.1	8.2	11.8	-	13.1	0.0 - 30.5
Amphibole	3.1	0.4	10.1	1.2	1.5	-	6.4	-	0.2	2.8	31.0	5.1	0.0 - 31.0
Scapolite	-	23.4	-	-	-	-	-	-	-	-	-	-	0.0 - 23.4
Phlogopite	-	1.0	3.4	18.8	10.5	-	-	0.2	2.7	-	0.4	-	0.0 - 18.8
Sphene	1.6	1.2	4.1	3.2	1.1	1.9	5.7	0.2	3.2	0.7	-	4.5	0.0 - 5.7
Apatite	-	tr.	0.3	-	0.1	0.1	1.3	-	-	0.1	-	0.8	0.0 - 1.3
Ore Minerals	2.5	5.6	2.5	8.4	2.9	9.6	3.3	0.4	8.2	4.2	8.6	1.8	0.4 - 9.6
Calcite	1.2	-	0.4	-	-	-	-	-	-	-	-	-	0.0 - 1.2
Serpentine & Chlorite	-	1.2	0.7	-	-	1.3	-	-	-	-	-	-	0.0 - 1.3

Table 19: Modal analyses of examples of the Dun Gott granulites.

Features of the individual constituent minerals are described below.

Plagioclase: The plagioclase is fresh or slightly sericitized and forms grains which are generally equant, but show some tendency to elongation parallel to the banding in occasional examples. Twinning is generally weak or absent but in one band examined albite and pericline twinning are clearly defined; the plagioclase of this band is also distinguished by having a composition in the albite range, whereas in all other examples examined the plagioclase is oligoclase or sodic andesine. Normal zoning is sometimes observed in plagioclase grains, and they occasionally contain anti-perthitic inclusions of potash felspar which may occur as little groups of blebs of uniform size or as inclusions quite irregular in shape and size. In examples of the granulites which contain appreciable amounts of potash felspar the plagioclase grains which are in contact with it often contain some myrmekitic intergrowths of quartz.

Potash Felspar: This variety of felspar is much more irregular in occurrence than the ubiquitious plagioclase, for, although it is completely absent or forms less than one per cent of the volume of more than half of the specimens of granulite examined in thin-section, in others it makes up over twenty-five per cent of the volume of the rock. The potash felspar, which is always fresh and sometimes displays cross-hatched twinning, occurs as small, irregularly outlined, interstitial grains in examples in which it is a minor constituent but forms equant grains, often aggregated together in microcline-rich bands, in those examples in which it occurs in important amounts. It often contains inclusions of sericitized plagioclase, which are sometimes in optical continuity with adjacent discrete grains of the same mineral. Occasional slender, tapering ribbons of fresh albite are also present as inclusions.

<u>Quartz</u>: Like the potash felspar, quartz is of very irregular occurrence; it may form equant or irregularly shaped grains within the matrix or large lobate grains elongated parallel to the banding of the rock. The quartz always shows strained extinction and some of the larger grains are crossed by transverse trains of tiny bubbles.

<u>Diopside</u>: Diopside is frequently an important constituent and makes up some thirty per cent of the volume of occasional specimens. It is most often colourless in section, but occasional examples are pale green and non-pleochroic. The mineral most often occurs as irregularly outlined xenoblastic grains concentrated in certain layers; occasionally it forms sub-idioblastic laths elongated parallel to the banding. In almost all examples examined, the diopside grains are mantled by and intergrown with a colourless amphibole and occasionally they are intergrown with sphene and ore. The diopside not infrequently shows lammellar twinning on (100) and its optical properties, $-2V\ 55^{\circ}$ to 58°, $N\alpha$ 1.665 and $N\gamma$ 1.692, are indicative of a pure diopside. (Hess, 1959)

<u>Amphibole</u>: This mineral is generally a minor constituent which mantles and is intergrown with diopside grains, but in one example examined it occurs in considerable amounts to the exclusion of diopside and, in this case, forms irregular laths, up to 3.0 mm. in length, elongated parallel to the banding of the rock. It is always fresh and generally colourless in section but

sometimes has a pale yellowish tinge. An example of the amphibole intergrown with diopside has $-2V$ 80°, $N\gamma$ 1.630, properties indicative of tremolite. (Deer et al., 1963)

Mica: Phlogopite occurs in about half of the specimens of granulite examined but generally in small amounts, and in only a very few cases does it constitute as much as ten per cent of the volume of the rock. It forms slender laths which may occur singly or be aggregated together in clusters, and which are generally elongated parallel to the banding. The phlogopite tends to be concentrated in bands in which diopside is scarce or absent. It is pleochroic from colourless to pale yellowish brown, and is generally fresh but sometimes partly altered to chloritic or serpentinous material. In one example of the granulites a few small ragged laths of foxy-red biotite occur.

Sphene: Sphene is found in almost all examples of the granulites, being absent only in those which also lack diopside. Its usual mode of occurrence is as swarms of tiny, watery brown, sub-rounded grains, which are concentrated especially in certain bands; but occasionally it forms much larger grains, up to 4.0 mm. in length, which are sub-idioblastic to idioblastic in outline and sometimes have cores of rutile. These larger sphene grains are markedly pleochroic from pale watery brown to light, slightly reddish brown.

Scapolite: Scapolite was observed in only two of the examples of granulite examined. In one of these examples, scapolite-rich and plagioclase-rich bands alternate, while in the other, bands rich in diopside alternate with bands containing both scapolite and plagioclase. The scapolite forms equant, xenoblastic grains and has refractive indices, $N_e = 1.547$, $N_o = 1.564$, which indicate a dipyre with a composition about Ma_{60}-Me_{40}.

Ore Minerals: Small irregular grains are generally present in small amounts and occasionally they make up as much as ten per cent of the volume of a specimen. The ore is sometimes intergrown with diopside, phlogopite, sphene or amphibole. Magnetite and pyrite are the species most commonly present.

Tiny, often sub-rounded, grains of apatite, and also calcite, serpentine and chlorite occur in accessory amounts.

An analysis of an example of the Dun Gott granulites executed by the Geological survey is quoted in Table 20. This rock was described as a diopside paragneiss "composed of irregular crystals of colourless diopside, allotriomorphic quartz and andesine felspar with some calcite, pyrites and graphite and abundant accessory sphene."

These Dun Gott granulites probably originated as banded dolomitic silts and shales. Most of the minerals present are likely to have been produced by isochemical reconstitution of material present in the original sediment; but the presence of bands in which grains of fresh potash felspar embay into and contain inclusions of, sericitized plagioclase, may indicate that there has been some metasomatic introduction of potash, while the occurrence of occasional bands containing abundant fresh albite may indicate some introduction of soda.

Metasomatic introduction of certain volatiles is often regarded as the cause of the development of scapolite in metamorphic rocks (Shaw, 1960)

SiO_2	49.37
Al_2O_3	17.18
Fe_2O_3	2.20
FeO	0.95
MgO	6.61
CaO	16.63
Na_2O	0.18
K_2O	1.67
H_2O +	0.96
H_2O −	0.14
TiO_2	1.25
P_2O_5	0.09
MnO	0.11
CO_2	2.65
FeS_2	0.21
C	0.09
	100.29

Table 20: Analysis of Diopside Paragneiss. Dun Gott Paragneiss series. 280 yds. W.32°N. of Dun Gott. (Guppy, 1931)

but in this case, where the occurrence of scapolite is confined to a few bands, it is possible that sufficient of the constituents necessary to convert plagioclase to scapolite were present in the original sediment. White (1959) quotes recent data which suggests that the halogen content of sediments is higher than was at one time believed to be the case; he considers that the scapolite content of certain lime rich metasediments from South Australia, somewhat similar to those at Dun Gott, originated as a result of isochemical metamorphism without introduction of volatiles.

The mantling of diopside by amphibole, seen in almost all the diopside bearing granulites, may indicate that pyroxene was formed during a period of maximum metamorphic intensity and that the amphibole formed later under milder conditions, or it may be that the pyroxene formed in a dry metamorphic environment and was subsequently partially converted to amphibole by the introduction of water, with or without a change in temperature.

(b) Marbles.

At Dun Gott, marbles and contorted calc-silicate rocks often occur in adjacent bands and grade into each other so that it is difficult to make an absolute division between them. However, for descriptive purposes it is convenient to separate them and from the accompanying table of modal analyses (Table 21) it will be seen that the rocks may be divided into forsterite bearing marbles, which contain negligible amounts of

Location of specimens featured in Table 21.

D-3-b : 87' E.10^{o}S. of the manse at Dun Gott.
D-3-d : Same locality as D-3-b.
D-17-b: At high water mark 380' E.10^{o}S. of the manse.
D-21-a: 750' E. of the manse.
D-21-d: Same locality as D-21-a.
D-22-g: Lens of marble enclosed by granulite; foreshore 440' N.30^{o}W. of Seann Charraig.
D-2-a : 860' E.10^{o}S. of the manse.
D-2-b : Same locality as D-2-a.
S-3-e : On the seaward side of the marble band at D-3-b.
D-18 : 450' E. of the manse.
D-20-c: 580' E.15^{o}S. of the manse.

	Marbles						Calc-silicates				
	D-3-b	D-3-d	D-17-b	D-21-a	D-21-d	D-22-g	D-2-a	D-2-b	D-3-e	D-18	D-20-c
Calcite & Dolomite	75.0	65.3	73.2	61.3	68.0	83.8	23.5	0.4	29.3	-	-
Pargasite	0.6	6.9	6.2	33.8	0.1	4.8	64.8	30.2	45.9	49.1	56.5
Phlogopite	6.5	15.5	5.8	0.1	3.6	-	-	-	1.3	0.7	-
Scapolite	-	-	-	-	-	-	-	17.2	12.3	41.8	10.8
Forsterite	8.0	10.7	7.8	2.3	0.1	11.2	-	-	-	-	-
Diopside	0.8	-	0.1	-	-	-	7.7	46.0	0.3	-	21.8
Plagioclase	-	-	-	-	-	-	0.2	-	7.4	-	0.8
Serpentine	8.4	0.9	2.1	-	25.4	-	-	-	-	-	1.8
Muscovite	-	-	-	-	-	-	tr.	-	-	-	-
Spinel	-	-	-	-	-	-	1.0	-	-	-	-
Sphene	-	-	-	-	-	-	-	0.2	-	1.3	tr.
Apatite	-	-	-	-	-	-	-	0.6	0.1	4.2	1.3
Ore Minerals	0.7	0.7	4.9	2.5	2.9	0.2	2.8	5.4	2.9	2.9	6.8
Quartz	-	-	-	-	-	-	-	-	0.5	-	-

Table 21: Modal analyses of specimens from marble and calc-silicate bands at Dun Gott.

scapolite and diopside, and forsterite free calc-silicate types which may still contain up to thirty per cent calcite and in which scapolite and diopside occur in important amounts.

The marbles occur either as bands up to about twenty feet in width or as lenses, up to about fifteen feet long and two feet wide, enclosed by the granulites; they are light grey rocks with a coarse, irregular weathering surface. The modal analyses of the marbles in Table 21 are of little quantitative value, for the mineralogy of these rocks is extremely variable, but they are a convenient way of illustrating the sort of assemblages found within them.

Features of the constituent minerals are described below:

<u>Calcite and dolomite</u>: The matrix of the marbles is a fairly even-grained mass of crystalline calcite and dolomite with grain sizes ranging up to 2.0 mm., which post-crystallization crushing has often reduced to a very finely granular mass. This crushing is often confined to certain narrow bands but sometimes all the carbonate within the area of a thin-section has been affected. The other constituent minerals of the marble also tend to be fragmented along bands of crushing but they are seldom as finely milled as the carbonates. In similar rocks in South Harris, Davidson (1943) was able to distinguish between calcite and dolomite in thin-section for the calcite grains were "nearly always clouded and turbid with a fine, indeterminate, opaque, brown dust", while the dolomite was "limpid and frequently idioblastic to the calcite"; but no such distinction has been observed between the two minerals in the present case.

However, staining with Lemberg's solution reveals that calcite is the dominant carbonate mineral and that both have been subjected to granulation, the calcite being generally more finely milled than the dolomite.

Amphibole: An amphibole, which is often colourless in section but occasionally has a pale yellowish tint, occurs in very variable amounts in the marble. It forms fresh, xenoblastic, sometimes sub-rounded grains which often wrap around forsterite grains. The amphibole has the following optical properties, +2V 75°, N α 1.627 and N γ 1.646. These properties are close to those of similar amphibole occurring in the crystalline limestone of South Harris which also wraps around forsterite grains and which proved, on analysis, to be an unusually lime-rich pargasite (Davidson, 1943).

Forsterite: This mineral occurs in the marbles in amounts varying from less than one per cent up to about ten per cent of the total volume. It is colourless and forms grains, mostly in the 0.25 to 2.0 mm. size range, which show all stages of replacement by serpentine from slight to complete and, as mentioned above, are occasionally mantled by amphibole. The optic angle, +2V, of the forsterite ranges from 82° to 86°.

Phlogopite: Phlogopite occurs fairly abundantly in crushed bands in the marbles but is generally sparse in the uncrushed portions. It is generally pleochroic with X colourless, Y and Z pale yellowish brown, and forms slender laths some 2.0 to 3.0 mm. in length which may occur singly or in clusters. These laths are often twisted and contorted and sometimes partly serpentinized.

Diopside: Diopside is absent or sparse in most of the marbles but occasional bands contain intergrowths of diopside and pargasite. The diopside is fresh and colourless, and forms xenoblastic to occasionally sub-idioblastic grains.

Spinel: Spinel occurs in only one of the thin sections of marble examined, where it forms occasional colourless, sub-rounded grains, 0.5 to 1.0 mm. in diameter, crossed by irregular cracks.

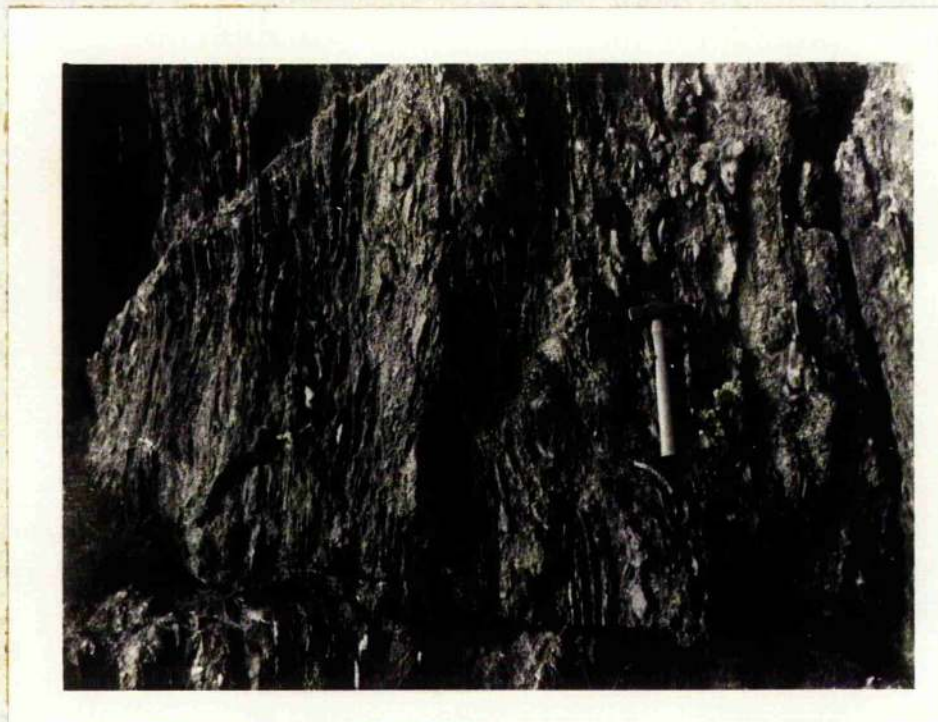
Irregular grains of ore up to 1.0 mm. in diameter and little flecks of graphite occur occasionally, and the crushed bands often contain some indeterminate fine grained opaque material.

The mineral assemblages in those bands of marble, namely calcite, dolomite, pargasite, forsterite, phlogopite, and minor amounts of ore, spinel and graphite, are similar to those which have been noted as the products of high grade regional metamorphism of dolomitic limestone from many parts of the world (Adams and Barow, 1910, Davidson, 1943, Tilley, 1920) and it seems likely that the original material of the sediment could supply the constituents necessary for the genesis of these minerals.

(c) Calc-silicate rocks.

The calc-silicate rocks are light grey in colour and form bands up to about twenty feet wide which have very irregular weathered surfaces and thin, often contorted, bedding. The irregular weathered surface typical of these rocks is illustrated in Plate 17. The calc-silicate rocks are interbanded with and grade into the marbles but, as stated

PLATE 18.



Calc-silicate rock at Dun Cott showing the irregular weathering surface typical of this type.

above, they differ from the marbles mineralogically by their lower content of calcite and dolomite, by the general presence of scapolite and by the presence of considerable amounts of diopside, a mineral which occurs in only accessory amounts in the marbles. The occurrence of diopside rather than forsterite indicates that silica was more freely available in these rocks during metamorphism than in the marbles.

Modal analyses of some examples of the calc-silicate rocks are included in Table 21 and features of the constituent minerals are described below.

Amphibole: An amphibole, weakly pleochroic from colourless to very pale yellowish brown, is generally the dominant mineral in the Dun Gott calc-silicates. It forms fresh, xenoblastic grains which vary in size from 0.1 to 3.0 mm. but which are generally of fairly uniform size in any one band and which show some tendency to elongation parallel to the banding. The amphibole has a +2V which varies from 70° to 78° and a typical example had $N\alpha$ 1.635 and $N\gamma$ 1.651, properties close to those of the lime-rich pargasite in the marbles.

Diopside: Irregularly outlined xenoblastic grains of diopside are an important constituent of most examples of the calc-silicate rocks. It is fresh and has optical properties which are indicative of a pure diopside, namely +2V 57°, $N\alpha$ 1.665 and $N\gamma$ 1.691.

Scapolite: Scapolite is almost always present in the calc-silicates and occasionally constitutes as much as forty per cent of their volume. It forms xenoblastic, generally equant, grains ranging from 0.2 to 0.5 mm. in size, which are sometimes evenly distributed within a thin-section but are often concentrated especially in certain bands. The scapolite is colourless and often shows partial alteration to rather fibrous micaceous material. The refractive indices of this scapolite, N_e 1.557 and N_o 1.587, together with its specific gravity of 2.87, indicate that it is a rather calcic mizzonite.

Plagioclase: Plagioclase is generally present in only accessory amounts but in one example examined it constitutes about ten per cent of the volume. In this example the plagioclase forms xenoblastic, generally equant grains, mostly in the 0.5 to 2.0 mm. size range, which are most often fresh and in which twinning is weakly developed or absent.

Calcite and Dolomite: These minerals are often absent but occasional carbonate-rich bands occur. Dolomite and calcite occur in approximately equal proportions in these bands and they are often crushed and granulated. The calcite is more finely-milled than the dolomite.

Ore Minerals: These occur in minor amounts as small, irregular grains and as intergranular films between diopside and pargasite grains.

Accessories: Minerals which occur sporadically in minor amounts are phlogopite, apatite, sphene, spinel, quartz and muscovite.

The mineral assemblages in these calc-silicate rocks are, on the whole, the normal products of the high-grade regional metamorphism of very impure dolomitic limestones (Davidson, 1943; Harry, 1951; Harker, 1932), but the occurrence of bands rich in scapolite may indicate that volatiles were introduced into these rocks along certain favoured channels.

However, the material necessary for the formation of scapolite may have been present in the original sediments and have become concentrated in certain layers during metamorphism.

(d) Quartzites.

Only two quartzite bands were observed amongst the metasediments at Dun Gott.

The first of these is a fairly massive band some ten feet wide of very fine-grained light greenish grey rock which is interbanded with calc-silicates and marbles at Port nan Caorach. In section it is seen to have a granoblastic texture with most constituent grains lying in the 0.05 to 0.2 mm. size range, and to be made up chiefly of rather irregularly outlined but generally more or less equant quartz grains which display strongly strained extinction and are generally free from inclusions. Xenoblastic grains of colourless diopside are common and they often show fine multiple twinning. Sometimes colourless amphibole is intergrown with them. The refractive indices of the diopside, $N\alpha$ 1.663 and $N\gamma$ 1.689, indicate that it is an almost pure variety of that mineral. Plagioclase and potash felspar occur fairly abundantly as small xenoblastic grains. The plagioclase is always more or less sericitized but the potash felspar is fresh and shows rather weakly developed cross-hatched twinning. There are many small grains and laths of graphite throughout the rock and also many, tiny, often sub-rounded, grains of sphene.

The other quartzite band, located near Seann Charraig, is also about ten feet wide and is a light grey, generally fine-grained rock. In section it is seen to be made up almost entirely of an interlocking mass of xenoblastic quartz grains, most of which lie in the 0.2 to 2.0 mm. size range, which are often crossed by trains of tiny bubbles and show strained extinction. Within this rock there occur occasional large, isolated laths up to 8.0 mm. in length of pyroxene which, in section, are medium bluish green and slightly pleochroic. Within these large grains there occur many tiny flecks, in mutual continuity, of a darker green, strongly pleochroic mineral, probably hornblende, and also tiny inclusions of ore and epidote.

These quartz-rich bands probably represent sandy layers in the original sediments.

(e) Graphite-Rich Rock.

At least one band of graphite-rich rock occurs amongst the metasediments at Dun Gott. The rock is medium grey, very fine to fine in grain and is often slightly schistose. In section it is seen to have granoblastic texture with constituent grains generally lying in the 0.1 to 1.0 mm. size range. Table 22 illustrates the sort of mineralogical assemblages found within this band. The individual constituent minerals are described below.

Graphite: Graphite occurs sometimes as irregular grains but more often as slender laths which show a fairly well-developed degree of parallel elongation along the banding. The graphite often has intergrown with it some colourless serpentinous material and occasionally some phlogopite.

Quartz: Quartz forms xenoblastic, equant grains which are generally

	D-1-a	D-21-b	D-26-c
Graphite	25.0	19.6	34.1
Quartz	33.8	39.6	33.2
Muscovite	34.6	-	16.0
Phlogopite	2.4	4.8	14.1
Plagioclase	-	13.6	-
K-felspar	-	22.6	-
Diopside	0.4	-	-
Pargasite	tr.	-	0.2
Sphene	1.0	-	0.4
Serpentine	2.8	-	1.8
Apatite	-	-	0.2

Table 22: Modal analyses of examples of the graphite-rich band at Dun Gott.

Location of specimens:

D-1-a : 870', E.15°S. of the manse at Dun Gott.

D-21-b: 690', E.10°S. of the manse.

D-26-c: 190' north of Seann Charraig.

free from inclusions and show slightly strained extinction. Although most of the quartz is very fine grained there are occasional porphyroblasts up to 6.0 mm. in length elongated parallel to the banding which also show strained extinction and are crossed by trains of tiny bubbles.

Muscovite and felspar appear to be mutually exclusive in the sections examined. When muscovite occurs it is colourless and forms rather stumpy laths which show little tendency to parallel elongation and are often rather fibrous. In the examples containing felspar both microcline and plagioclase are present. The former is fresh, shows some cross hatched twinning and often contains some slender tapering inclusions of albite, while the latter is generally partially or completely sericitized.

Phlogopite: Minor amounts of phlogopite occur forming tiny laths, pleochroic from colourless to pale brown, which show a strong tendency to orientation parallel to the banding. It is sometimes partially chloritized.

Small grains of diopside, pargasite, sphene and apatite occur in accessory amounts.

This graphite-rich band is likely to have originated as a bed of carbonaceous silt or shale.

(f) Amphibolites.

Several bands of amphibolite occur associated with the metasediments of Dun Gott.

The amphibolites are medium grey, fine to medium grained, rocks which are weakly banded and sometimes somewhat schistose.

In section they are seen to have an xenoblastic granular texture, with constituent grains generally lying in the 0.5 to 1.0 mm. size range, although garnet porphyroblasts much larger than this occur in occasional bands. Modal analyses of some examples of the amphibolites are given in Table 23 and it will be observed that hornblende and plagioclase are the most important constituents in all examples. Important amounts of garnet and quartz occur in some bands and minor amounts of pyroxene are generally present along with accessory biotite, ore and apatite. Descriptive notes on the constituent minerals are given below.

Hornblende: Hornblende forms grains which, when in mutual contact, show some development of crystal faces, but are generally embayed when they abut against plagioclase or pyroxene. It is generally fresh and is strongly pleochroic with X pale brownish green, Y medium brownish green and Z medium or dark brownish green. Examples of the hornblende had the following optical properties: (1) $-2V\ 79^{\circ}$, $N\alpha$ 1.645, $N\gamma$ 1.667

(2) $-2V\ 76^{\circ}$, $N\alpha$ 1.651, $N\gamma$ 1.671

Plagioclase: Plagioclase forms xenoblastic, equant grains which often embay into hornblende grains and sometimes contain some small inclusions of the latter mineral, little groups of which are occasionaly optically continous. The plagioclase is an andesine with a composition ranging from An_{30} to An_{42}. Albite and pericline twinning are occasionally well developed but often weak or absent, and normal zoning can be observed in a few grains. The plagioclase is generally fresh.

Orthopyroxene and Clinopyroxene: The two types of pyroxene occur in

	D-16-a	D-18-b	D-23	D-24-b
Hornblende	40.5	67.4	37.1	48.3
Plagioclase	39.6	31.4	23.9	15.0
Clinopyroxene & Orthopyroxene	16.0	0.8	8.7	6.3
Garnet	-	-	17.3	29.5
Quartz	-	-	10.7	0.8
Biotite	3.7	0.4	0.3	0.1
Ore Minerals	-	tr.	2.1	-
Apatite	-	tr.	-	0.1
Colourless Amphibole	0.2	-	-	-

Table 23: Modal analyses of amphibolites from Dun Gott.

Location of specimens:
D-16-a: 565' N.25°E. of the manse.
D-18-b: Just above the high water mark, 225' N.25°E. of the manse.
D-23 : 400' W.30°N. of Seann Charraig.
D-24-b: 220' W.25°N. of Seann Charraig.

varying minor amounts forming xenoblastic grains which are often intergrown with each other and sometimes with the hornblende. The pyroxene grains frequently contain small inclusions of hornblende, and in one example the clinopyroxene grains contain inclusions of hornblende and are rimmed by a very pale green, almost colourless amphibole. Both the pyroxenes are generally colourless but occasionally the orthorhombic variety displays just perceptible pleochroism from colourless to pale pink.

Garnet: The garnet forms very irregularly outlined porphyroblasts which are often elongated in the direction of the banding. Occasionally these porphyroblasts may be up to 15.0 mm. in length but generally do not exceed 4.0 mm. in breadth. The garnet is pale pink in section and contains many poeciloblastic inclusions of quartz, plagioclase, hornblende, ore and biotite. The refractive index of the garnet is 1.785 and its specific gravity 3.94 properties which, when compared with Winchell's diagrams (Winchell, 1951) suggest an almandine-pyrope containing about 65 molecular per cent pyrope and perhaps some grossularite.

Quartz: Quartz occurs only in these bands which also contain garnet. It forms xenoblastic, generally equant, grains which show strained extinction and are often crossed by trains of tiny bubbles.

Biotite: Biotite, strongly pleochroic from pale to deep reddish brown, occurs in minor amounts forming small laths which are generally orientated approximately parallel to the banding of the rocks and which cut through plagioclase, hornblende and pyroxene grains. The biotite is fresh.

The difficulty encountered in attempting to distinguish between ortho and para-amphibolites is commented on elsewhere in this thesis when the origin of the basic gneiss of Balephetrish Hill is discussed. These amphibolites at Dun Gott, which are associated with granulites and marbles of undoubted sedimentary origin, could have originated as basic sediments such as dolomitic shale, as basic lava flows, as beds of tuff, or as minor intrusions; the petrography offers no clues as to which of these possibilities is the most likely.

(g) Garnet-Biotite-Schist.

The garnet-biotite-schist is a medium purplish-grey rock within which occur pale grey quartzo-felspathic streaks and bands. It exhibits weak to moderate schistosity which coincides with the banding. Modal analyses of two examples of this rock are given in Table 24.

The matrix is generally made up of a granoblastic mass of interlocking plagioclase and quartz grains, most of which lie in the 0.5 to 2.0 mm. size range. The plagioclase is an oligoclase with a composition of An_{20} and it displays fairly well developed albite and sometimes pericline twinning and slight normal zoning. The quartz forms irregularly outlined grains which show undulatory extinction.

Biotite, strongly pleochroic from pale to dark reddish-brown, forms rather ragged laths up to 2.0 mm. in length which are often aggregated together in clusters and are generally elongated parallel or sub-parallel to the schistosity. It is quite fresh and contains small inclusions of ore; these occur as granules and as strips along the cleavages of the biotite.

	D-14-a	D-16-d
Garnet	19.4	32.3
Biotite	30.7	34.1
Plagioclase	27.5	12.7
Quartz	21.5	19.1
Apatite	0.1	-
Ore	0.8	1.6

Table 24: Modal analyses of garnetiferous biotite schist from Dun Gott.

Locations of specimens:
D-14-a: 920' N. 15° W. of the manse.
D-16-d: 530' N. 25° E. of the manse.

Garnet, which is a very faint purplish colour in thin-sections, forms xenoblastic, irregularly outlined but generally equant porphyroblasts up to about 5.0 mm. in diameter. These often contain many small laths of biotite, blebs of quartz and tiny rods of ore mineral. The biotite laths, rods of ore and sometimes the quartz grains included within any one garnet grain often show parallel elongation, but this direction may vary slightly in different garnet grains although it is always within 20° of the direction of the schistosity. Often garnets are especially rich in inclusions in their centres but have a zone completely free of inclusions around their margins.

Apatite occurs as rare, tiny sub-rounded grains.

As well as the granoblastic quartz and felspar in the matrix of the schist there occur also distinct quartzo-felspathic rich bands containing minor biotite. These bands, which vary from a fraction of an inch to two or three inches in width, run parallel to the schistosity and are slightly coarser grained than the main mass of the rock.

An analysis of garnet biotite schist from Dun Gott is quoted below. This rock probably originated as ferruginous silt or shale. The distinct garnet-free, biotite-poor, leucocratic bands may represent arenaceous streaks in the original sediment or may owe their origin to the segregation or addition of quartso-felspathic material during metamorphism.

(2) CAOLES.

Along the east coast of Tiree, around the crofting community of Caoles,

SiO_2	59.71
Al_2O_3	15.45
Fe_2O_3	6.99
FeO	5.96
MgO	4.93
CaO	1.66
Na_2O	0.66
K_2O	1.60
H_2O+	0.60
H_2O-	0.04
TiO_2	1.83
P_2O_5	0.04
MnO	0.06
CO_2	0.12
FeS_2	0.51
	100.16

Table 25: Analysis of: "Garnet gneiss, Dun Gott paragneiss series. 125 yds. W.42°N. of Dun Gott. Composed of andesine, quartz, abundant biotite and accessory iron ore". (Guppy, 1931)

there occur many bands and blocks of metasediments within the Banded Migmatite and Leucogranitic Gneiss. These rocks are best exposed at Rudha Dubh, a headland near Rossgill House, and good exposures occur also at Port Ban and Sgeir Ghobhlach.

At Rudha Dubh, inclusions of marble, calc-silicate rock, granulite and quartzite occur in the Leucogranitic Gneiss. These inclusions form bands, either continuous or made up of a series of separate, irregular blocks, which are generally extended parallel to the banding of the enclosing Leucogranitic Gneiss and which vary in width from a few inches to several feet. Although the bands of metasedimentary inclusions are usually parallel to the banding of the enclosing gneiss, sometimes there occur elongated blocks of quartzite quite oblique to that banding. These quartzite blocks often have abrupt terminations approximately at right angles to the presumed sedimentary banding within them and appear to have been broken off larger bodies, probably during plastic movement of the enclosing rock. The metasediments are sometimes in direct contact with the enclosing gneiss but often are mantled by a layer of acid pegmatitic material which grades within a few inches into the gneiss. This coarse-grained acid material has irregular but sharp contacts against the metasediments and ramifies through joints and fissures within them. (Plate 19)

The following types of metasediment occur at Rudha Dubh.

(a) Calc-silicate rock

(b) Granulite

(c) Marble

(d) Quartzite

PLATE 19.

Calc-silicate block enclosed in Leucogranitic Gneiss at Rudha Dubh. The rule rests on the calc-silicate rock which is mantled and penetrated by pegmatitic acid material.

These are now described separately below:

(a) <u>Calc-silicate rock.</u>

This is the most commonly occuring metasedimentary type at Rudha Dubh. It occurs as rows of irregular, light to medium greenish grey blocks within which faint banding is generally visible. This banding is most often parallel to the banding of the enclosing gneiss but occasionally oblique to it. In section, diopside is seen to be the principal constituent mineral of the calc-silicate rock, making up approximately three-quarters of the volume of most examples and forming grains of all shapes and sizes from completely xenoblastic granules around 0.25 mm. in diameter up to sub-idioblastic laths some 5.0 mm. long and 2.0 mm. broad. It is colourless and fresh, and contains many inclusions of, and is occasionally intergrown with, an amphibole pleochroic from colourless to pale green. It also contains small inclusions of quartz and felspar. All the amphibole inclusions within a single diopside grain are generally in optical continuity. The optical properties of the diopside, $+2V\ 57^{\circ}$, $N\alpha$ 1.672, $N\gamma$ 1.702, correspond with those of an intermediate diopside (Hess, 1949) while those of the amphibole, $-2V\ 83^{\circ}$, $N\alpha$ 1.621, $N\gamma$ 1.642, along with its pale colouration, indicate actinolite (Winchell and Winchell, 1951). Xenoblastic grains of plagioclase, mostly in the 0.5 to 2.5 mm. size range, are an important constituent in some examples. The plagioclase is sometimes partly sericitized but some albite twinning can generally be observed and occasionally some normal zoning. It is an andesine in the An_{40} to An_{50} range. Very minor amounts of quartz occur as interstitial grains and there are some very small, sub-rounded apatite laths.

(b) Granulites.

These are fine-grained, faintly banded, pale greenish grey rocks which occasionally occur associated with the calc-silicate blocks. In section they are seen to have a xenoblastic granular texture with grain sizes in the 0.25 to 1.0 mm. size range.

Felspar constitutes approximately sixty per cent of the volume of most examples. Potash felspar is the dominant variety but small patches in which plagioclase occurs, sometimes to the complete exclusion of potash felspar, can occasionally be seen in sections. The potash felspar is fresh and displays shadowy extinction and some weakly defined cross-hatched twinning. It often embays into the diopside grains and occasionally includes sericitized fragments of plagioclase. The plagioclase, in which twinning is weakly developed or completely absent, is often partly sericitized, but when a sericitized grain abuts against potash felspar it has a narrow, completely clear rim in most cases.

The diopside is colourless and fresh and generally forms irregular xenoblastic grains, mostly of the same order of size as the felspar; but it occasionally forms slender sub-idioblastic laths, up to 5.0 mm. in length, elongated parallel to the banding.

Phlogopite, pleochroic from colourless to pale brown and often partly chloritized, occurs in accessory amounts and there are rare tiny grains of apatite.

(c) Marble.

A block of light greenish grey, faintly banded Marble some fifty feet long and five feet broad occurs in the Leucogranitic Gneiss at Rudha Dubh, elongated parallel to the banding of that rock.

Microscopically the marble is seen to be made up of a mosaic of xenoblastic calcite and dolomite grains, mostly in the 0.5 to 1.5 mm. size range, in which are embedded grains of diopside and minor amounts of felspar and mica. Staining with Lemberg's solution revealed that the calcite greatly predominates over the dolomite. The diopside, which constitutes from five to ten per cent of the volume of the marble, is colourless and fresh and forms xenoblastic, often sub-rounded, grains from 0.25 to 0.75 mm. in diameter in which there occasionally occur inclusions of amphibole, pleochroic from colourless to pale green. Potash felspar forms occasional xenoblastic grains from 0.25 to 0.5 mm. in diameter which often show shadowy extinction and sometimes very weakly developed cross-hatched twinning. Clusters of slender phlogopite laths up to 2.0 mm. in length occur in occasional bands. The phlogopite is pleochroic from colourless to pale brown and sometimes partially chloritized.

(d) Quartzite.

The quartzite is a fine, even-grained rock which is faintly banded in shades of light to medium greenish grey. It is generally closely associated with calc-silicate rock and, indeed, some of the metasedimentary blocks are made up partly of calc-silicate rock and partly of quartzite. In thin-section, the quartzite is seen to be made up almost entirely of a granoblastic mass of quartz, the grain size of which ranges from 0.5 to 2.5 mm. The quartz all shows severely strained extinction but there is no development of mortar structure. The grains are occasionally crossed by trains of tiny bubbles. Minor amounts of felspar occur within the quartzite. Plagioclase forms xenoblastic grains from 0.1 to 0.3 mm. in diameter which all are more or less sericitized; while the potash felspar occurs as small, irregularly outlined, interstitial grains, which sometimes show very weakly developed cross-hatched twinning. The potash felspar is fresh. Small flakes of phlogopite, pleochroic from colourless to pale brown, and irregularly outlined small grains of amphibole, pleochroic from colourless to very pale green, occur rather sparsely, and the slight colour banding seen in hand specimens of this rock is due to the segregation of these two minerals in alternate layers of the rock. Small, sub-rounded grains of apatite occur throughout and there are several partially altered grains of clinozoisite.

Along the coast south of Rudha Dubh blocks of similar metasedimentary rocks occur occasionally in the Leucogranitic Gneiss and at the small inlet of Port Ban blocks of quartzite and calc-silicate rock are well exposed. In the calc-silicate blocks there is some banding due to the alternation of diopside-rich and actinolite-rich layers.

On the foreshore of Sgeir Ghobhlach, which is about a mile north-west of Rudha Dubh but still in the Caoles area, there occur some blocks and bands of calc-silicate rock, in this case included in Banded Migmatite. These rocks are very much like those described from Rudha Dubh but bands rich in scapolite can occasionally be observed in the calc-silicate blocks.

These metasedimentary rocks at Caoles are, on the whole, the normal products of the regional metamorphism of impure dolomitic limestones, dolomitic shales and silts. It does not seem necessary to postulate the introduction of any extraneous material except, perhaps, in the case of those bands in the granulites in which fresh microcline, which embays into the diopside and plagioclase grains and contains sericitized inclusions of the latter, is the dominant mineral, where some accession of potash may have taken place. Scapolite occurs only very occasionally in the Rudha Dubh rocks and once again it seems possible that sufficient of the constituents necessary to effect its genesis could have been present in the original material of the sediments.

(3) BALEPHETRISH.

Balephetrish is the best known geological locality in Tiree, for it is here that the well known Tiree Marble occurs and was once quarried as an ornamental stone. Macculloch (1819) gave an early description of its field appearance; and its petrography and mode of occurrence were described by Coomaraswamy (1903), who concluded that the mineral assemblages of the marble resulted from contact metamorphism effected by the intrusion of the adjacent gneisses. Hallimond (1947) has published a detailed mineralogical account of two specimens from Balephetrish, one of typical pink pyroxene marble and the other of a block of gneiss-like rock included in the marble and composed of pyroxene, amphibole, mica, and scapolite with some coarsely crystalline calcite. Analyses reveal that the pyroxene from the marble is very close to a pure diopside but that the pyroxene from the gneiss-like inclusion contains a substantial amount of alumina, 4.74%, being classed by Hallimond as a fassaite, an old name revived by Tilley for certain aluminous pyroxenes with full content of calcium from Ceylon and Monzoni (Tilley, 1938). The amphibole from the gneiss-like inclusions was found to be a calciferous type with a good deal of replacement of silicon by aluminium and was classed as pargasite by Hallimond.

The pink marble at Balephetrish occurs in a small disused quarry one hundred yards south-east of Balephetrish House, and on the shore at Port a Cheim three hundred yards north-west of the house. Many outcrops of light grey marble occur in a field on the south side of the road from Balephetrish to Scarinish, approximately one hundred yards south-east of Balephetrish House. The occurrences at each of these localities are described below.

(a) Balephetrish Quarry.

In the small quarry at Balephetrish the marble forms a band some twenty feet wide which has irregular but sharp contacts with the Banded Migmatite enclosing it on either side. Prominent flow lines can be observed within the marble and these are more or less parallel to its contacts with the Banded Migmatite; occasional narrow veins of flinty crush occur within the migmatite adjacent to the contacts and parallel or sub-parallel to them.

The marble here is a pale pink, fine-grained rock in which are embedded many greenish-black pyroxene grains. Microscopically, it is seen to consist of a mass of triturated carbonate, which staining with Lemberg's solution reveals to be almost entirely calcite; in this matrix occur scattered grains of diopside and minor amounts of amphibole and mica. The diopside forms xenoblastic, often sub-rounded, laths up to about 3.0 mm. in length which are colourless or very pale green and often display fine polysynthetic twinning on (100). Its optical properties are: +2V 57°, N α 1.675, N γ 1.700. The amphibole is weakly pleochroic in shades of pale green and occurs as irregularly outlined, sometimes sub-rounded, usually fresh grains up to about 2.0 mm. in size, which sometimes occur in aggregates with the diopside. Phlogopite, pleochroic from colourless to pale yellowish brown, occurs as irregular, sometimes contorted, laths which are often elongated parallel to the banding and sometimes cling to the margins of diopside grains.

In the marble close to the contacts with the Banded Migmatite there occur many small rounded grains, up to about 0.2 mm. in diameter, of colourless, strongly birefringent, scapolite, which are occasionally slightly sericitized. Some sub-rounded grains of sphene up to about 0.25 mm. in length and very occasional small, sub-rounded plagioclase grains are also found in the marble close to these contacts. The contact between the migmatite and marble on the south side of the marble band was examined in thin-section. It was found that the dark zone from 5.0 to 10.0 mm. wide which marks the contact is made up of a very finely granular aggregate of quartz, plagioclase and potash felspar in which occur abundant, very irregularly outlined grains of hornblende, pleochroic from pale to medium olive green and often crossed by diffuse bands of fine black dust. Fine flakes of biotite, pleochroic from pale to deep reddish brown, are often intergrown with the hornblende and there are occasional tiny, xenoblastic diopside grains. This junction of the marble and the migmatite seems likely to be a tectonic one and the narrow band of finely granular material, just described, along the contact between them was probably produced by the grinding down of some of the migmatite adjacent to the contact.

(b) Port a Cheim.

The Leucogranitic Gneiss which makes up the bulk of this headland is cut by several minor, east-west trending faults and is often shattered, showing some planes of slickensiding. The bright orange-red colour, which is a striking feature of the gneiss here, is caused by the accumulation of fine red dust, probably of iron oxide, in the microscopic bands of crushing which ramify through the rock.

Within this mass of Leucocratic Gneiss there occur some irregularly outlined bodies of marble with some associated calc-silicate rock, the dimensions of which are very variable but seldom exceed some thirty feet. The contacts between the marble and the Leucogranitic Gneiss and between the marble and the calc-silicate rock are very irregular; the marble sometimes contains detached blocks of Leucogranitic Gneiss and calc-silicate rock which are generally irregular but sometimes sub-rounded in outline, and which have their longest axes elongated parallel to the flow banding in the marble. The dimensions of these blocks range from two or three inches to about two feet. Sometimes a layer of diopside-rich calc-silicate rock two or three inches wide occurs along the contact between marble and Leucogranitic Gneiss. In one case a remarkable tectonic breccia some four feet thick occurs at the junction of the marble and Leucogranitic Gneiss. It consists of a light grey matrix of finely milled marble in which are embedded many irregular, sometimes sub-rounded, blocks of Leucogranitic Gneiss, pegmatite, amphibolite, quartz and calc-silicate rock, ranging up to four feet in diameter. This breccia is illustrated in Plate 20.

The marble at Port a Cheim is similar to that at Balephetrish quarry, again being a fine grained pink rock in which single grains and clusters of calc-silicate minerals occur, the grains often being sub-rounded in outline and up to two or three inches in diameter. Microscopically, the marble is again seen to have a matrix of finely milled calcite and dolomite, the former being greatly predominant, in which occur many xenoblastic, often sub-rounded grains of colourless diopside, up to 2.5 mm. in diameter. These sometimes have associated with them some irregular flakes of amphibole, pleochroic in shades of pale green. The diopside has +2V 57°, Nα 1.672 and Nγ 1.698. Little flecks of pale phlogopite often cling to the periphery of the diopside grains and some ragged laths of this mineral occur occasionally elsewhere in the rock.

The calc-silicate aggregations in the marble consist mainly of diopside, which is often intergrown with minor amounts of pale green amphibole, but they occasionally contain patches in which scapolite is the predominant

PLATE 20.

Tectonic breccia at Port a Cheim. The breccia is overlain by Leucogranitic Gneiss and underlain by marble.

mineral. The scapolite forms a mosaic of sub-idioblastic laths up to 1.0 mm. in length which are often heavily sericitized. The refractive indices of the scapolite, N_e 1.550 and N_o 1.581, indicate a composition about $Ma_{40}Me_{60}$. Small rounded apatite grains occur occasionally, and there are rarely some small xenoblastic felspar grains. Some calcite occurs within these aggregations and, unlike the calcite and dolomite in the general body of the rock, it has escaped granulation and forms xenoblastic to sub-idioblastic grains up to 1.5 mm. in size. These calc-silicate aggregations may mark the loci of siliceous nodules in the original dolomitic limestone.

The larger, somewhat gneissose, blocks of calc-silicate rock, irregular in outline and up to two feet in diameter, are made up mineral assemblages similar to those of the calc-silicate aggregates described above; they probably represent fragments of calc-silicate bands which were broken up by plastic movement of the marble during the period of deformation when it was granulated and acquired flow banding.

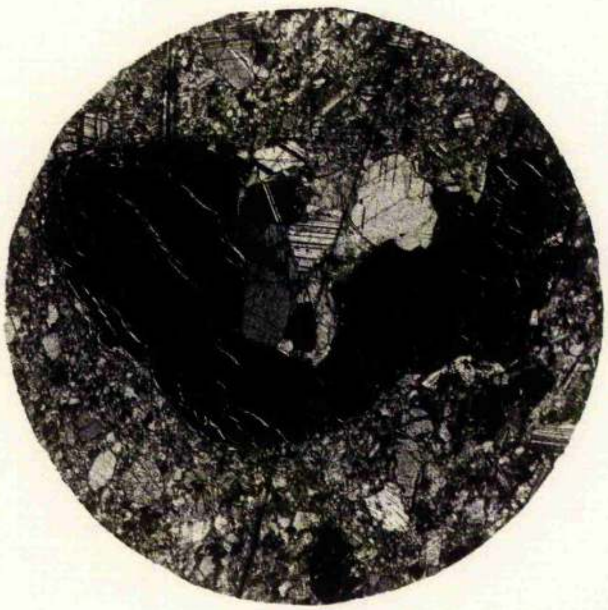
On Traigh Beagh, the small beach just north of Port a Cheim, there occur some outcrops of pale greenish grey calc-silicate rock, Leucogranitic Gneiss and pegmatite. These rocks are very contorted and have apparently undergone severe deformation together. An example of the calc-silicate rock was found to be made up almost entirely of colourless diopside with only minor intergrowths of pale green amphibole and occasional ore grains. The diopside forms a mass of sub-idioblastic grains from 1.0 to 8.0 mm. in size which sometimes show multiple twinning on (100); its optical properties, +2V 59° $N\alpha$ 1.670 and $N\gamma$ 1.697, are those of a pure diopside.

The complex nature of the relationship of the marble to the enclosing gneiss at Port a Cheim must be due to movement which affected these rocks after the main period of metamorphism; most of the contacts are likely to be tectonic. Occasionally, however when the marble abuts against the granitic gneiss, a layer of calc-silicate minerals a few inches thick lies along the contact; in these cases the contact is perhaps one which existed before metamorphism and across which some siliceous material migrated a few inches into the marble during the migmatitization of the adjoining rocks. Elsewhere, the existence of blocks of gneiss within the marble orientated with their longest axes parallel to its banding, and of the tectonic breccia illustrated in Plate 20, are convincing proof that the gneiss and marble have suffered deformation together and that, during this process, the marble has behaved in a plastic fashion, detaching and sweeping away blocks of gneiss and also of calc-silicate rock. That the crushing and flowage of the marble was later than the regional metamorphism is evinced by the fact that the calcite and dolomite within clusters of calc-silicate minerals or within embayments in a single calc-silicate grain, in otherwise finely granulated marble, are quite uncrushed; they must have been protected by the presence of the calc-silicate minerals which are a product of the regional metamorphism.

(c) <u>South of the Scarinish Road.</u>

The marble which occurs in scattered outcrops in the field south of the road from Balephetrish to Scarinish, about a thousand yards from Balephetrish House, differs from the types described above in that it is white or light

PLATE 21.



Grey marble at Balephetrish. The large dark grain is forsterite. The carbonate which lies within the embayment in the forsterite is seen to have escaped the trituration which has affected the surrounding material. (X 15, crossed nicols) grey rather than pink, and contains significant amounts of forsterite, a mineral lacking in the Balephetrish Quarry and Port a Cheim occurrences. This grey marble has pronounced flow lines and contains conspicuous aggregates of calc-silicate minerals several inches in diameter. In thin section, the marble is seen to have been severely crushed, although not as finely milled as the pink varieties described above. Dolomite appears to have been somewhat more resistant to crushing than calcite and xenoblastic grains of the former, up to 1.0 mm. in diameter, occur set in a much more finely granular matrix of the latter. Carbonate grains which occur within embayments in forsterite grains are seen to have been protected from crushing. This is illustrated in Plate 21. The forsterite forms xenoblastic, sometimes sub-rounded grains from 0.5 to 4.0 mm. in diameter which abound throughout the marble and are sometimes aggregated together in clusters. They are sometimes slightly serpentinized peripherally and along the irregular cracks which dissect them. There are occasional, often sub-rounded, laths of diopside up to 1.0 mm. in length and very occasionally some flakes of colourless mica.

<u>Origin</u>: Coomaraswamy considered the mineral assemblages found in the marbles around Balephetrish to be the products of high temperature contact metamorphism of original dolomitic limestones, and regarded the adjacent acid gneisses as the metamorphosing agency. However, the assemblages are similar to those which have been accepted as the normal products of the regional metamorphism of impure dolomitic limestones in other areas (Davidson, 1943; Harker, 1932; Harry, 1951; Tilley, 1920) and it does not seem necessary to

postulate any process other than this to account for the mineralogy of most of these rocks; nevertheless, the diopside-rich layers, two or three inches wide, found along certain of the marble-gneiss contacts, suggest shallow penetration of the marble by siliceous material during the migmatitization of the adjoining rocks, and the concentration of scapolite close to the margin of the body of pink marble in Balephetrish quarry, may point to some introduction of volatiles during the same process.

(4) VAUL BAY.

On the west side of this bay there occur some bands of garnetiferous gneiss and calc-silicate rocks similar to those described from Dun Gott. These need not be discussed in detail. At the east side of the bay at the end of the small beach, Traigh Bhalla, a band of metasedimentary rocks some ten feet wide is found within the Banded Migmatite. Within this metasedimentary band there occurs a rock with some unusual and interesting textural features.

This is a medium-grained pink, felspathic rock in which scattered grains of pale green pyroxene and occasional quartz grains can be observed in hand specimen. It forms a band some three feet wide, enclosed by a two feet wide quartzite layer on one side and a five feet wide marble and calc-silicate layer on the other.

Microscopic examination of this rock reveals that potash felspar constitutes approximately seventy per cent of its volume, diopside fifteen per cent, and vesicle-like bodies composed of quartz and calcite ten per cent.

Minor amounts of quartz occur within the felspar matrix outwith these vesicle-like bodies and there are accessory amounts of sphene, epidote, amphibole and apatite. The alkali content of this rock, as determined on the flame photometer, is 0.75 per cent Na_2O and 9.10 per cent K_2O.

The potash felspar has an optic angle, -2V, ranging from 68° to 76° and forms a mass of xenoblastic grains mostly from 0.5 to 2.5 mm. in size. In many cases they are clouded by a very fine brown dust, although a few grains are quite clear. Twinning is usually absent but some weakly developed cross-hatching can occasionally be observed, while some grains are crossed by slender parallel bands of dust perhaps representing the traces of albite twinning in earlier plagioclase which has now been completely made over to potash felspar. Many of the felspar grains show zoning and some contain groups of narrow tapering albite inclusions which, within a single felspar grain, are mutually parallel and optically continuous. The occasional quartz grains within the felspar matrix are of the same order of size as the felspar grains and have completely irregular xenoblastic outlines. They show strongly strained extinction.

The diopside, a very pale green variety, occurs as irregularly outlined, xenoblastic and often embayed grains from 0.25 to 1.5 mm. in size, showing a development of crystal faces only when they are in mutual contact in the small diopside aggregations which sometimes occur. Minor amounts of amphibole, pleochroic from pale to light, slightly bluish-green, occurs partially mantling, and often intergrown with, some of the diopside grains. The optical properties of the diopside, +2V 56.5°, $N\alpha$ 1.672, $N\gamma$ 1.702, indicate that it is fairly pure.

The vesicle-like bodies mentioned above are the most interesting and unusual feature of this rock. These bodies are often irregularly outlined and somewhat lobate in form but they occasionally have a narrow rectangular shape suggesting that they may be pseudomorphous after some lath-shaped mineral. The irregularly outlined examples are somewhat elongate and measure up to 4.0 mm. while those with rectangular form seldom exceed 1.5 mm. in length. Mineralogically these bodies consist of an aggregate of xenoblastic quartz and calcite grains in proportions which vary greatly in different examples although, on the whole, quartz is dominant. The quartz is only very slightly strained, much less so than the quartz grains which occur in the matrix of the rock. When this 'vesicular' quartz abuts against enclosing felspar grains tiny stumpy laths and needles of very pale green epidote grow out from the felspar into the quartz; often some of the little epidote needles are detached and appear to be 'floating' in the quartz. In places where these epidote needles and laths are absent, the felspar has a rather frayed brown margin against the quartz. When the 'vesicular' quartz abuts against diopside rather than felspar the epidote is absent, but a row of little quartz blebs forms along the boundary and these sometimes have sharp terminations pointing in towards the centre of the 'vesicle'. When 'vesicular' calcite abuts against felspar epidote needles are sometimes present but when the calcite is in contact with diopside no special phenomenon marks the junction.

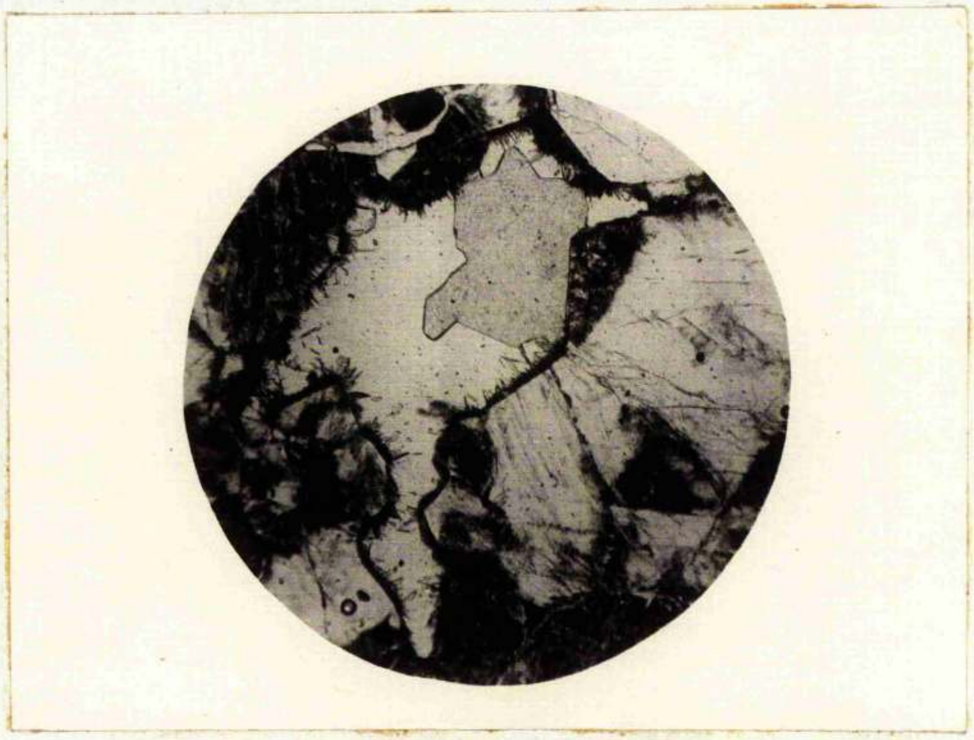
Plate 22 illustrates one of the irregularly shaped 'vesicles' while

PLATE 22.

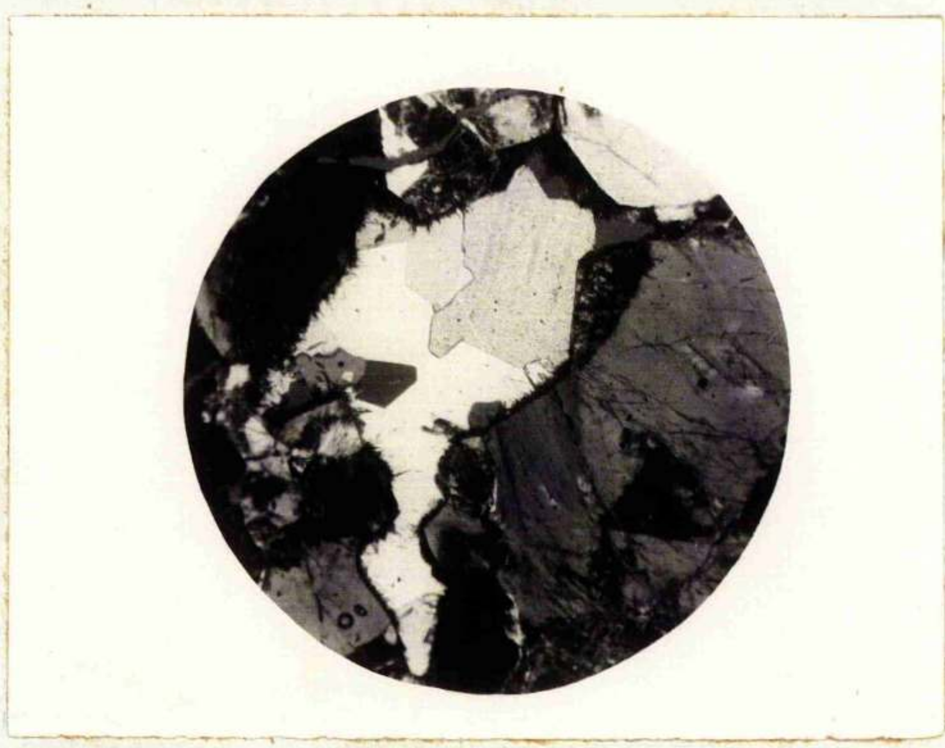
A. Vesicular-like structure made up of quartz and calcite within the diopside-potash felspar metasedimentary rock from Vaul Bay. Fine epidote needles grow into the quartz from the surrounding potash felspar grains. (X 25)

B. The same. (X 25, crossed nicols)

PLATE 22.



A.



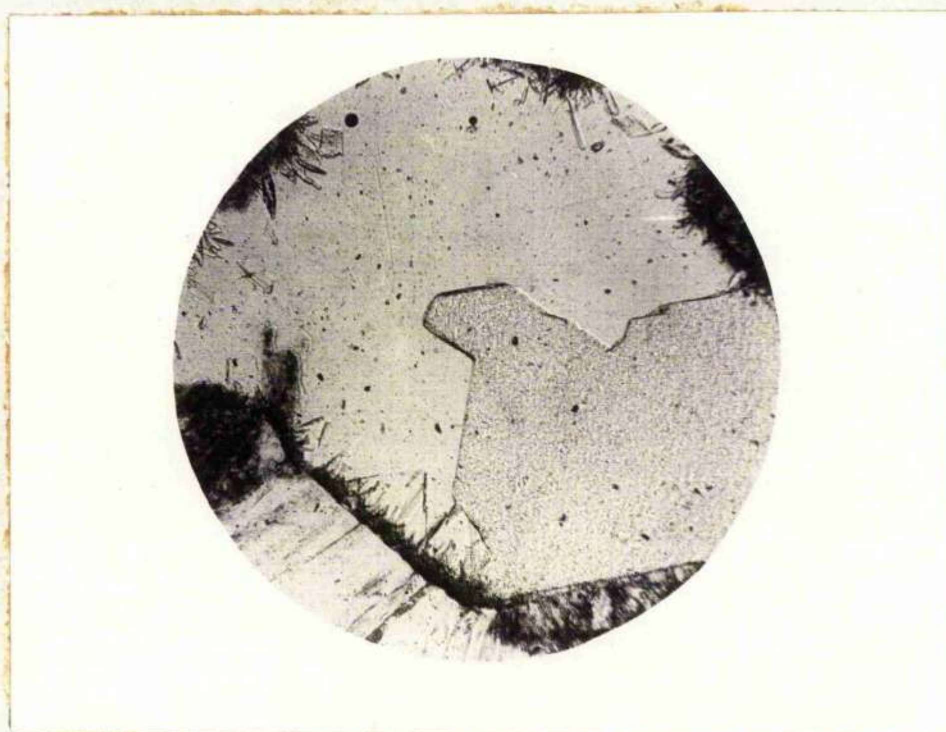
B.

PLATE 23.

A. A higher magnification of a portion of the structure illustrated in Plate 22. (X 60)

B. Another of the vesicular-like structures in the Vaul Bay diopside-potash felspar rock. This example has a rectangular outline and is made up wholly of quartz. It is surrounded by potash felspar, from which epidote needles grow, except in the north-west quadrant where it abuts against a diopside grain; small sub-idioblastic quartz crystals cling to the diopside (X 25, crossed nicols)

PLATE 23.



A.

B.

Plate 23-B illustrates an example with a rectangular outline. These textural features are similar to those already described from the albite-rich basic gneiss at Creagan Mora (Plate 11) but no record of similar features observed in gneissose rocks elsewhere has been found in the literature.

The rock also contains occasional, xenoblastic to sub-idioblastic grains of faintly pleochroic, watery brown sphene, which are from 0.2 to 0.8 mm. in size and sometimes occur in little optically continuous groups. Occasional small rounded apatite grains, heavily coated with fine brown dust, like that clouding many of the felspar grains, can be observed.

Since this rock is interbanded with marble and quartzite and has a mineral assemblage suggesting a composition quite unlike that of any igneous rock, it is considered to be of ultimate sedimentary origin. Shales very rich in potash which have an alkali content similar to that determined for this rock are known (Gruner & Thiel, 1937) but are rather rare, and this rock may owe its high potash content to an influx of potash during the migmatitization process. Positive evidence is not available to help one decide whether the potash content was present in the rock prior to metamorphism and migmatitization or whether it was wholly or partly added during those processes; but the presence of the narrow parallel lines of dust in some of the potash felspars may, as suggested above, represent the traces of albite twinning and indicate that some at least of the potash felspar has formed at the expense of plagioclase.

The mode of origin of the 'vesicle-like' structures is uncertain. They are believed to have formed, or at least to have attained their present condition, after the main cycle of metamorphism and deformation, for the quartzite adjacent to the 'vesicular' rock on one side is heavily sheared while the marble on the other side is finely-milled; it seems unlikely that such delicate textural features as these 'vesicles' could have survived the severe stresses which these rocks must have undergone. The quartz in the 'vesicles' is only slightly strained while the quartz in the matrix of the enclosing rock is heavily strained; this suggests that the former is of later origin.

In the adjacent marble bending and disruption of diopside and phlogopite are often observed demonstrating that here, as at Dalephetrish, the marble was subjected to stress after regional metamorphism. Therefore, since the quartz in the 'vesicles' has been shown to be likely to have originated after the period of stress, it must also be later than the regional metamorphism. The only clue to the origin of the 'vesicles' is the fact that, as illustrated in Plate 19-B, they occasionally have a rectangular outline; it may be that the quartz and calcite are filling spaces created by the leaching of some earlier mineral which formed lath-shaped grains.

The marble adjacent to the 'vesicular' rock is a finely-milled, pale pink variety which has some calc-silicate layers associated with it. It consists of a matrix of triturated calcite in which occur many diopside and phlogopite grains. The diopside is colourless and forms sub-idioblastic, and sometimes sub-rounded, grains from about 0.1 to 3.0 mm. in diameter; these have often been subjected to bending and partial disruption. The phlogopite is colourless and forms rather ragged, often contorted, laths up to 2.0 mm. in length which sometimes wrap around diopside grains, a textural feature also observed in the marbles at Balephetrish. Some of the phlogopite is altered to colourless chlorite with very weak birefringence. There are occasional small, sub-rounded grains of apatite; these are often clouded by a fine brown dust.

The quartzite band which abuts against the 'vesicular' rock on its east side is a fairly massive, light grey rock in which there occur irregular, pink felspathic patches. In thin-section the rock is seen to be composed of an intricately interlocking mass of irregularly shaped quartz grains up to 8.0 mm. in size; these are often dissected by narrow bands of finely granulated quartz and they display undulose extinction. Occasional xenoblastic felspar laths occur; these are generally sericitised but some show albite twinning, the extinction of which, together with the refractive indices, indicate that the felspar is in the oligoclase compositional range. There are occasional small flakes of penninite, containing many minute inclusions of ore, and rare sub-rounded zircon granules.

(5) RINGING STONE.

The Ringing Stone is a large glacial erratic of Tertiary gabbro or eucrite bearing 'cup' markings of archaeological interest; it lies on the north shore between Balephetrish and Vaul. Within a few yards of it there occurs a body of metasedimentary rocks some fifteen feet wide, consisting of alternating bands of quartzite and diopside-rich calc-silicate rock with minor streaks of marble. The banding of these metasediments is concordant with that of the enclosing Banded Migmatite, although along the contacts between the metasediments and the migmatite there is some contortion of the former, together with irregular pegmatite injection, suggesting that there has been some movement along the plane of contact.

The quartzite is similar to the example described above from Vaul Bay in field appearance but in thin-section it is seen to have been much more severely sheared and to consist mainly of elongate, tapering lenses of strained quartz separated by narrow bands of finely granulated quartz. Some of the larger quartz lenses contain groups of tiny dark needles, apparently of random orientation. There are common xenoblastic, sometimes sub-rounded, laths of plagioclase around which the narrow bands of granulated quartz curve and which, themselves, sometimes show some peripheral granulation. The plagioclase, which is fresh and often displays well-developed albite twinning, is in the andesine compositional range. There are also very occasional grains of potash felspar and some tiny fragments of epidote.

The calc-silicate bands are made up of medium to dark greenish grey rock which is composed almost entirely of irregularly orientated, xenoblastic laths of colourless diopside mostly between 1.0 and 4.0 mm. in size. The optical properties, +2V 60.5, $N\alpha$ 1.670 and $N\gamma$ 1.703, are those of an almost pure diopside. Phlogopite, pleochroic from very pale to medium yellowish brown, occurs fairly abundantly as irregularly outlined laths up to 2.0 mm. in length which often contain small ore grains and are sometimes partially chloritized. Amphibole, pleochroic from colourless to light olive green, forms irregular grains which sometimes appear to be mantling the diopside, and it also occurs occasionally as irregular groups of small inclusions in mutual optical continuity within the diopside grains. Sometimes these small inclusions of amphibole have some phlogopite associated with them. The amphibole has $-2V$ close to 90°, $N\alpha$ 1.649 and $N\gamma$ 1.664. Occasionally these diopside rich rocks grade into narrow bands of diopside marble.

(6) LOCH A' PHUIL.

Some seventy five yards from the north-west corner of Loch a' Phuil, on the east side of a stone wall which runs approximately parallel to the shore of the loch, there outcrops a band of magnetite-pyroxenite from ten to twelve feet wide, which grades into garnet-biotite-gneiss on its east side and dark, hornblende pyroxene gneiss on its west side. The geophysical survey carried out by Whetton and Myer (1949) revealed that this band of magnetite-rich rock continues almost completely across the island from Balephuil Bay on the south coast to Loch Bhasapoll about a mile from the north coast. At Loch Bhasapoll it terminates against a band of flinty crush. According to the interpretation of the geophysical data, the magnetite-rich band is of fairly uniform thickness throughout its length. However, it branches just south of Loch a' Phuil, giving rise to two subsidiary narrower bands which continue north in a direction sub-parallel to that of the main band to Barrapoll, about half a mile north of Loch a' Phuil, where they die out against a minor fault.

The pyroxenite is a fine to medium grained, dark grey rock in which faint banding parallel to the trend of the surrounding rocks can be observed. In section it is seen to consist predominantly of clinopyroxene, accompanied by considerable amounts of magnetite and minor apatite. The clinopyroxene forms xenoblastic to sub-idioblastic grains, generally from 1.0 to 3.0 mm. in size, and either colourless or very pale watery brown. It is fresh and free from inclusions, except for occasional specks of ore, and has optical properties, +2V 40° to 43°, $N\alpha > 1.71 < 1.72$, $N\gamma > 1.73 < 1.74$ and $Z\hat{\ }c$ 42°, which are very similar to those of a ferroaugite from a dolerite pegmatite in East Griqualand, an analysis of which is quoted by Deer et al. (1963). The magnetite forms irregularly outlined, sometimes skeletal, grains of the same order of size as those of the pyroxene, which are sometimes mantled by a narrow film of an indeterminate, pale brown, isotropic substance. Apatite occurs as narrow laths, often with sub-rounded terminations, which are up to 1.0 mm. in length and generally elongated parallel to the banding. Modal analyses of two examples of this rock are given in Table 26 and its texture is illustrated in Plate 24.

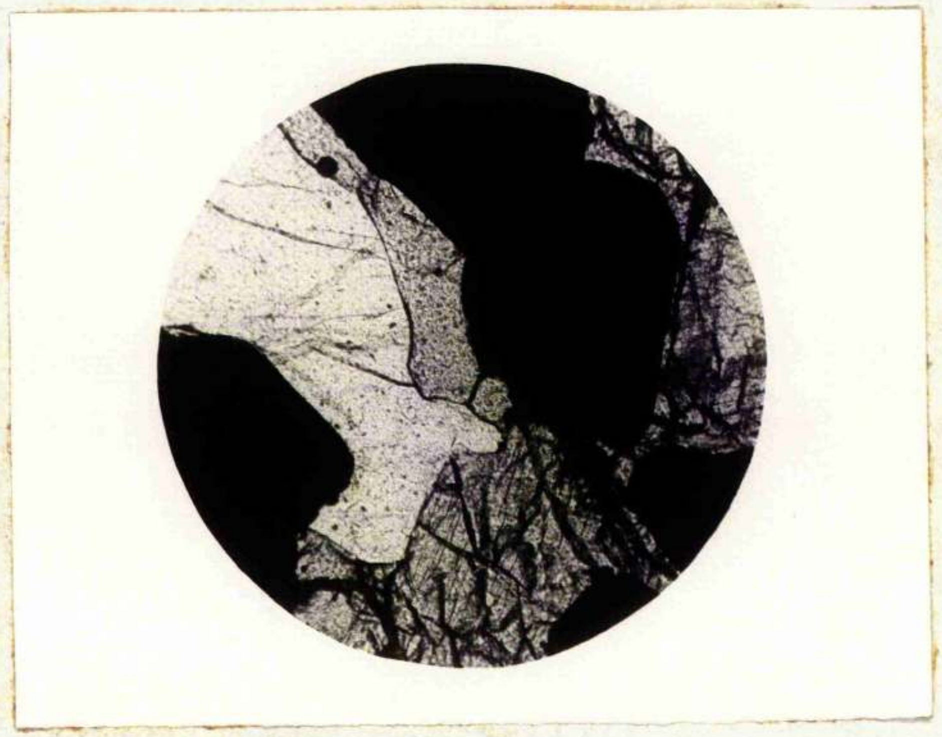
The garnet-biotite-gneiss into which the pyroxenite grades has a fine-grained quartzo-felspathic matrix in which are set porphyroblasts of garnet and laths of biotite. The matrix has a grain size of from 0.5 to 1.5 mm. and is composed of a xenoblastic mosaic of quartz, plagioclase and potash felspar. The quartz grains show well-marked strained extinction; those of potash felspar also display strained extinction, are untwinned and contain occasional groups of tiny lens-shaped perthitic plagioclase inclusions. The plagioclase grains are generally slightly sericitized, occasionally

	D-35	D-36
Clinopyroxene	65.6	74.7
Magnetite	30.3	25.1
Apatite	2.8	-
Rims around Magnetite	1.3	0.2

Table 26: Modal analyses of magnetite-pyroxenite from Loch a Phuil.

Both specimens are from the outcrop at the north-west corner of the loch.

PLATE 24.



Magnetite pyroxenite from the outcrop near Loch a Phuil. The black grains are of magnetite; colourless apatite can be observed in the left half of the picture and clinopyroxene grains, crossed by irregular cracks, occur in the right half. A layer of the pale brown isotropic substance, described in the text, is seen to mantle the magnetite in the upper half of the picture. (X 25) display albite twinning and, when they abut against potash felspar, contain some myrmekitic quartz intergrowths. The plagioclase is an oligoclase. The garnet is pale purple in thin-sections and forms sub-rounded porphyroblasts up to 8.0 mm. in diameter, the centres of which are often crowded with poeciloblastic inclusions of quartz and ore. Its refractive index is close to 1.790 and its specific gravity is 3.98, properties which indicate that it is a variety in which almandine is dominant and lesser amounts of pyrope and grossularite occur. The biotite is strongly pleochroic from pale to deep reddish brown and forms clusters of laths up to 2.0 mm. in length which often grow around the margins of garnet grains and sometimes have some ore intergrown with them. Stringers of biotite occasionally occur along cracks within the garnet porphyroblasts.

This garnet biotite gneiss is likely to have been produced by the regional metamorphism of a pelitic sediment and, since the magnetite-pyroxenite grades into it, it seems reasonable to postulate a sedimentary origin for that rock also.

METAMORPHIC FACIES OF THE METASEDIMENTS.

Mineral assemblages observed in the more commonly occuring metasedimentary rock types in Tiree are listed below:

1. Granulites

(a) Plagioclase; diopside; ± phlogopite; ± scapolite; with minor amounts of tremolite, sphene, apatite, calcite and ore.

(b) Plagioclase; potash felspar; diopside; with minor amounts of tremolite, phlogopite, apatite, calcite and ore.

(c) Plagioclase; potash felspar; quartz; ± diopside; with minor amounts of tremolite, sphene, apatite, phlogopite and ore.

2. <u>Marbles</u>

(a) Calcite; dolomite; forsterite; tremolite; phlogopite; with minor amounts of ore, scapolite, diopside and rarely spinel.

(b) Calcite; dolomite; diopside; with minor amounts of tremolite, phlogopite, scapolite and sphene.

3. <u>Calc-Silicate Bands</u>

Diopside; actinolite; ± scapolite; ± plagioclase; ± potash felspar; ± phlogopite.

4. <u>Amphibolites</u>

Plagioclase; hornblende; clinopyroxene; orthopyroxene; ± garnet (almandine-pyrope); ± quartz; with minor amounts of biotite, apatite and ore.

5. <u>Garnet Biotite Gneisses</u>

Garnet (almandine-pyrope); biotite; plagioclase; quartz; ± potash felspar; with minor amounts of ore and apatite.

Textural evidence suggests that much of the pale amphibole which occurs in types 1, 2, and 3 above formed at the expense of forsterite and diopside, either as a result of an easing of conditions after the main period of metamorphism or of an introduction of water with or without a change in temperature. In either case the amphibole can be disregarded when attempting to decide what sort of conditions prevailed during the period of maximum metamorphic intensity: when the amphibole is thus eliminated, the assemblages in these three types are somewhat similar to those considered indicative of the hornblende granulite subfacies of the granulite facies, while the occurrence of perthitic and anti-perthitic intergrowths in the felspars is also suggestive of granulite facies conditions. Sphene, a frequently occurring accessory in the granulites, was at one time (Turner and Verhoogen, 1951) thought to be invariably absent in granulite facies assemblages but more recently Turner (in Fyfe et al., 1958) has listed sphene, along with scapolite and phlogopite, as being common accessories in the newly defined hornblende granulite subfacies. The presence of dolomite in the marble bands indicates that the conditions of Bowen's fifth step (Brown, 1940) were not attained and, therefore, the temperatures prevailing during metamorphism are not likely to have exceeded 700°.

The association of hornblende with clinopyroxene and orthopyroxene observed in the amphibolite bands within the enclave of metasediments at Dun Gott is indicative of crystallization in the hornblende granulite subfacies (Fyfe et al., 1958). Biotite, a phase which would not be expected to appear in a basic assemblage belonging to that subfacies, occurs in minor amounts, but textural evidence suggests that it formed later than the hornblende, pyroxenes and garnet and its presence probably indicates slight diaphthoresis after the period of granulite facies metamorphism.

Turner (1958) has said that there is nothing to distinguish pelitic and quartzo-felspathic assemblages of the hornblende granulite subfacies from those of the almandine amphibolite facies, and therefore the assemblages observed in the bands of garnet biotite gneiss may belong to either of these; but their close association with the pyroxene-bearing amphibolite bands discussed above permits them to be assigned to the hornblende granulite subfacies. Textural evidence suggests that the biotite has, in part, formed at the expense of the garnet and it may be that, in this case also, the biotite is, at least in part, of diaphthoretic origin.

The evidence suggests, therefore, that the metasediments have undergone regional metamorphism under hornblende granulite subfacies conditions and that after this high grade metamorphism had been achieved, slight diaphthoresis took place in certain bands. It is believed that the metamorphism was essentially an isochemical process although there may have been some introduction of potash into bands now very rich in potash felspar. The occurrence of concentrations of phlogopite along crushed bands in the Dun Gott marbles may indicate that shearing took place most readily along micaceous bands.

PART V

SUGGESTED HISTORY OF THE LEWISIAN ROCKS OF TIREE

SUGGESTED HISTORY OF THE LEWISIAN ROCKS OF TIREE.

Sutton and Watson (1950) in their account of the Lewisian rocks of the Loch Torridon and Scourie areas of the mainland of Scotland, have presented evidence which indicates that these rocks have been affected by two distinct cycles of metamorphism, migmatitisation and deformation seperated by a long interval of time. A series of dolerite dykes was intruded during the interval between the two metamorphic cycles.

Although certain aspects of the work of Sutton and Watson have been challenged by Bowes (1962) and others, the fundamental point that the mass of gneisses collectively designated as Lewisian represents the products of not one but at least two, and probably more, metamorphic cycles is now well established and confirmed by the geochronological work of Gilleti et al. (1961).

However, no matter how many metamorphic cycles may have affected some portions of the Lewisian, there may exist others in which the gneisses have been affected by a single cycle. An area of gneiss might, for example, have been metamorphosed during an early cycle but have remained outwith the zones of influence of all subsequent cycles; or the penultimate metamorphic cycle in a given area might have been followed by a period of geosynclinal sedimentation the products of which would be affected by the final cycle but show no traces of any previous ones. During the present examination of the Tiree rocks no evidence necessitating the postulation of more than one major cycle of metamorphism and migmatitization has been observed.

The earliest event recorded by the rocks of Tiree appears to be a period of sedimentation during which the material now preserved in the metasedimentary bands was laid down together with large amounts of greywackes and related sediments. Some of the concordant bands of basic and ultrabasic gneiss, such as those described from Kilkenneth and Ceann a Mhara, may have originated at this time as lavas or tuffs; the presence of some bands of albite-rich basic gneiss at Creagan Mora suggests that some of the lavas were spilitic.

After sedimentation it is believed that folding took place; for basic lenses, in which isoclinal folds occur and are truncated by the enclosing acid material, are included in the Banded Migmatite. One such lens is shown in Plate 4-A.

Following the folding there occurred a period of igneous intrusion. The broad basic bands, such as those described in detail from Ballymartin and Port na Moidhaig, which are elongated parallel to the banding of the migmatite but locally transgress it (Plate 5-B), were probably intruded at this time. The material which now constitutes the intermediate gneiss mass of Ben Hough was perhaps emplaced during the same period as a dioritic plug.

The rocks were then buried at considerable depth and metamorphism and migmatitization took place. Temperatures and pressures were high enough to promote the genesis of mineral assemblages typical of the lower subfacies of the granulite facies in the 'resister' bands of basic, ultrabasic and metasedimentary rock; but most of the mass was migmatitized by the action of migrating aqueous solutions and in these 'wet' rocks upper almandine amphibolite facies assemblages were engendered. The aqueous solutions which promoted migmatitization may have been made up from water originally present in the rocks, which was being driven out in response to the severe metamorphic conditions; but some of it may have migrated into the rocks, perhaps having been driven out of rocks being metamorphosed at even greater depth. Insufficient chemical data are available to enable the nature of the migmatitization process to be ascertained, however, the present information suggests that it may have been essentially endomigmatitic, except perhaps for some introduction of alkalies. The general parallelism of the banding in the migmatites with that in the metasediments suggests that migration of the solutions took place most readily along s-surfaces which probably represented original bedding or sedimentary banding.

The rocks penetrated by the migmatitizing solutions were rendered much more plastic than the bands and lenses of 'resister' rock; these 'resisters' were often broken up by mobile felsic material. Features such as wildfolding and agmatitic breccias within the migmatites suggest that certain portions become exceptionally plastic, presumably because they contained unusually large amounts of water. The curving of the banding of the migmatite around blocks of basic and ultrabasic rock suggests that the migmatite underwent compression while in a plastic state. The numerous pegmatitic bands may have originated at this time, and perhaps owe their origin to the accumulation of the migmatitizing fluid at certain favoured loci or to local anatexis.

The presence of the migmatitizing fluid facilitated diffusion and the marginal zones of large ultrabasic lenses become enriched in lime, silica, alumina and alkalies and depleted in iron and magnesium (Figure 7). Although the fluid did not extensively penetrate the broader basic bands its presence apparently inhibited the genesis of granulite facies assemblages in their marginal zones (Figures 3 and 5). Felspar porphyroblastesis took place in the albite-rich basic gneiss at Creagan Mora when stress was declining but temperatures were still high and fluid still available to facilitate diffusion.

At some time after the migmatitization, when the rocks had lost their plasticity but were still probably deeply buried, faulting took place and caused the formation of occasional bands of flinty crush, the most important of which runs from The Green to Kilkenneth. It is likely that the granulation and the development of flow banding in the marbles around Balephetrish took place at this time.

Minor faults trending approximately east-west occasionally affect the Lewisian rocks and a marked reddening of the rocks, due to the development of a fine network of iron oxide veins, is usually observed for a few feet on either side of them. Since these faults are seen to displace Tertiary dykes they can confidently be dated as post-Tertiary and probably took place at shallow depth.

A tentative interpretation of the sequence of events which have affected the Lewisian rocks of Tiree, arrived at by correlation of the field and laboratory evidence, is presented overleaf in tabular form.

This cycle of events is broadly similar to those postulated in many

		Event	Product
Time	Elevation	Post-Tertiary movements at shallow depth.	Minor east-west faults .
		Tertiary intrusions.	Dyke swarm.
		Deep-seated movements.	Zones of shattering and flinty crush; trituration of marbles.
	Depression	Metamorphism and Migmatitization.	Granulite facies assemblages in 'resister' bands. Amphibolite facies assemblages in migmatites.
		Period of igneous intrusion.	Basic bands and irregular basic bodies. Dioritic mass of Ben Hough.
		Folding.	Isoclinal folds observed within basic lenses included in the Banded Migmatite.
		Geosynclinal sedimentation.	Greywackes, shales, dolomites, lavas (spilitic ?), etc.

Table 27: Suggested geological history of the Lewisian rocks of Tiree.

other regions of Precambrian gneisses and migmatites (Eckelmann and Poldervaart, 1957; Ward, 1959; Harris, 1959; Read, 1957). The intrusion of basic rocks during the folding and depression of the geosynclinal sediments, but prior to their metamorphism and migmatitization, is considered to be a characteristic feature of such cycles. Read says that: "..... mafic magma may be produced from the simatic downbuckle to supply the diabases of the orthogeosynclinal piles and those of the dyke swarms that appear to precede many plutonic cycles." and that: "..... such dyke swarms may indeed prepare the crust for migmatization and the like."

On the evidence available it is not possible to correlate the cycle of metamorphism and migmatitization which has affected the Tiree rocks with either the Scourian or Laxfordian cycles which Sutton and Watson (1951) consider to have affected the Lewisian rocks of the Scottish mainland. If the dyke-like basic bands described in detail (q.v., pp. 43 - 66) were considered to be equivalent to the Scourie dykes of the mainland, which are considered to have been intruded during the interval between the Scourian and Laxfordian periods of metamorphism, then the metamorphic cycle in Tiree could be correlated with the Laxfordian since it has resulted in the metamorphism of these basic bands. However, although the chemical composition of these basic rocks is somewhat similar to the published analyses of Scourie Dykes (O'Hara, 1961), the evidence is not strong enough to support such a correlation. Dearnley (1962) compared the basic rocks which form intrusions in the Lewisian complex of the Outer Hebrides with the Scourie dykes and considered the two to be genetically related for the following reasons:

"(1) They are both basic differentiates of tholeitic nature.

(2) They have both undergone a granulite-facies metamorphism in the different degrees of intensity.

(3) They are both seen in some areas to cut a granulite-facies complex and in other areas to have been subjected to a later folding and retrograde metamorphism of the same date."

Discussing the first of these reasons, Bowes (1962) has pointed out that "..... tholeitic magmas will be geochemically similar whatever the age of intrusion." The second point also seems to be of little correlative value, for granulite facies conditions may have prevailed at several different times in different parts of the Lewisian complex; because two sets of chemically similar basic rocks show similar metamorphic mineral assemblages it cannot be assumed that these assemblages originated during the same metamorphic cycle. Dearnley's third point is based on the geochronological work of Gilleti <u>et al</u>., (1961), who have shown that the retrograde metamorphism and migmatitization in the Outer Hebrides is contemporaneous with the Laxfordian cycle of the mainland. However, although the basic rocks of the islands and the Scourie dykes of the mainland may thus be shown to have undergone retrograde metamorphism at the same time this does not imply that the main prograde metamorphism was necessarily contemporaneous nor that the two sets of basic rocks are 'genetically' related.

Dearnley's correlation of these two sets of basic rocks, upon which, along with structural evidence, he postulates the existence of a Minch fault with a displacement of some 77 miles, cannot, therefore be regarded as as conclusive. It is considered that definite correlations between the Lewisian of the mainland and the Hebridean occurrences will not be possible until much more geochronological information is available.

APPENDIX

THE CHARNOCKITE PROBLEM

THE CHARNOCKITE PROBLEM.

The name charnockite was first applied by Holland (1900) to a hypersthene-bearing granite from southern India and the term charnockitic was used by him to describe the intermediate, basic and ultrabasic rocks associated with it in the field, all of which contain a rhombic pyroxene and have a granulitic texture. Although Holland expressed the wish that the terms charnockite and charnockitic should be applied to rocks outside India only when they could be shown to have genetical affinities with those of the type area, the terms have in fact been generally applied to hypersthene-bearing suites of rocks throughout the world whatever their hypothecated origin; a large volume of literature now exists in which the nature and origin of such rocks is discussed. This literature has been reviewed by Quesnel (1951), Parras (1958) and, most extensively, by Picamuthu (1953), who refers to the question of the origin of these rocks as the 'charnockite problem'.

Charnockitic rocks have been found to be confined to Precambrian shield areas and, in most cases, to have strong textural as well as mineralogical affinities with the type-rocks of India; but their mode of occurrence is variable for they may form large homogeneous bodies, inhomogeneous banded gneisses containing basic schlieren, and dyke-like basic bands or ultrabasic lenses and bands. Their genesis has been variously ascribed to magmatic intrusion and differentiation (Holland 1900, Buddington, 1939), metamorphism of a series of plutonic rocks (Groves, 1935) and to the metamorphism of sedimentary rocks (Ghosh, 1941). It seems that, as Pichamuthu has said, there are charnockites and charnockites, and that the free use of the terms charnockite and charnockitic has resulted in their being applied to rocks of very diverse origins and histories. The terms, therefore, have lost all genetical connotation and have become descriptive names which merely indicate that a suite of rocks, to which they are applied, contains ubiquitous hypersthene and has certain textural features in common with the rocks described by Holland.

In the description of the Tiree rocks it was noted that the Massive Migmatite, the Pen Hough Intermediate Gneiss and the basic rocks included in the Banded Migmatite are mineralogically and texturally analogous to the acid, intermediate and basic members of the charnockitic series respectively; while the ultrabasic gneisses at Ceann a Mhara and Kilkenneth have strong affinities with the ultrabasic members of that series. Since the mineral assemblages typical of the charnockitic rocks, as well as certain textural features such as perthitic, anti-perthitic and myrmekitic structures in the felspars, are also those indicative of granulite facies metamorphism (Fyfe et al., 1958), the charnockitic rocks of Tiree appear simply to be those which have undergone 'dry' granulite facies metamorphism as opposed to the relatively 'wet' amphibolite facies metamorphism which has affected the adjacent migmatites.

The 'dry' and 'wet' assemblages grade into each other in the marginal zones of some basic bands and at the junction between the Massive Migmatite and the Banded Migmatite with little change in the bulk composition of the rocks. It appears therefore, that in this area at least, no distinct 'charnockite problem' exists and that the origin of the charnockitic rocks is inextricably involved in the origin and history of the Lewisian rocks of Tiree as a whole. In fact diverse origins are postulated in this thesis for the charnockitic rocks: the Massive Migmatite is thought perhaps to represent a highly altered mass of sedimentary material; the basic rocks within the Banded Migmatite to have originated as minor intrusions; the Ben Hough gneiss to have originated as a dioritic mass; and the ultrabasic gneisses to have, perhaps, originated as 'oceanitic' type lavas. The feature which those rocks have in common is that they appear to have been deficient in water during the metamorphism and migmatitisation of the complex, either because of an initial low water content, or because they were impervious to penetration by the migmatitizing fluids; or to a combination of both these factors. They have therefore recrystallized as 'dry' assemblages except when they are marginally modified by proximity to 'wet' amphibolite rocks. It would, therefore, hinder rather than facilitate the study of these rocks to consider their origin as a separate 'charnockite problem' without reference to their relationship to the other Lewisian rocks with which they are associated.

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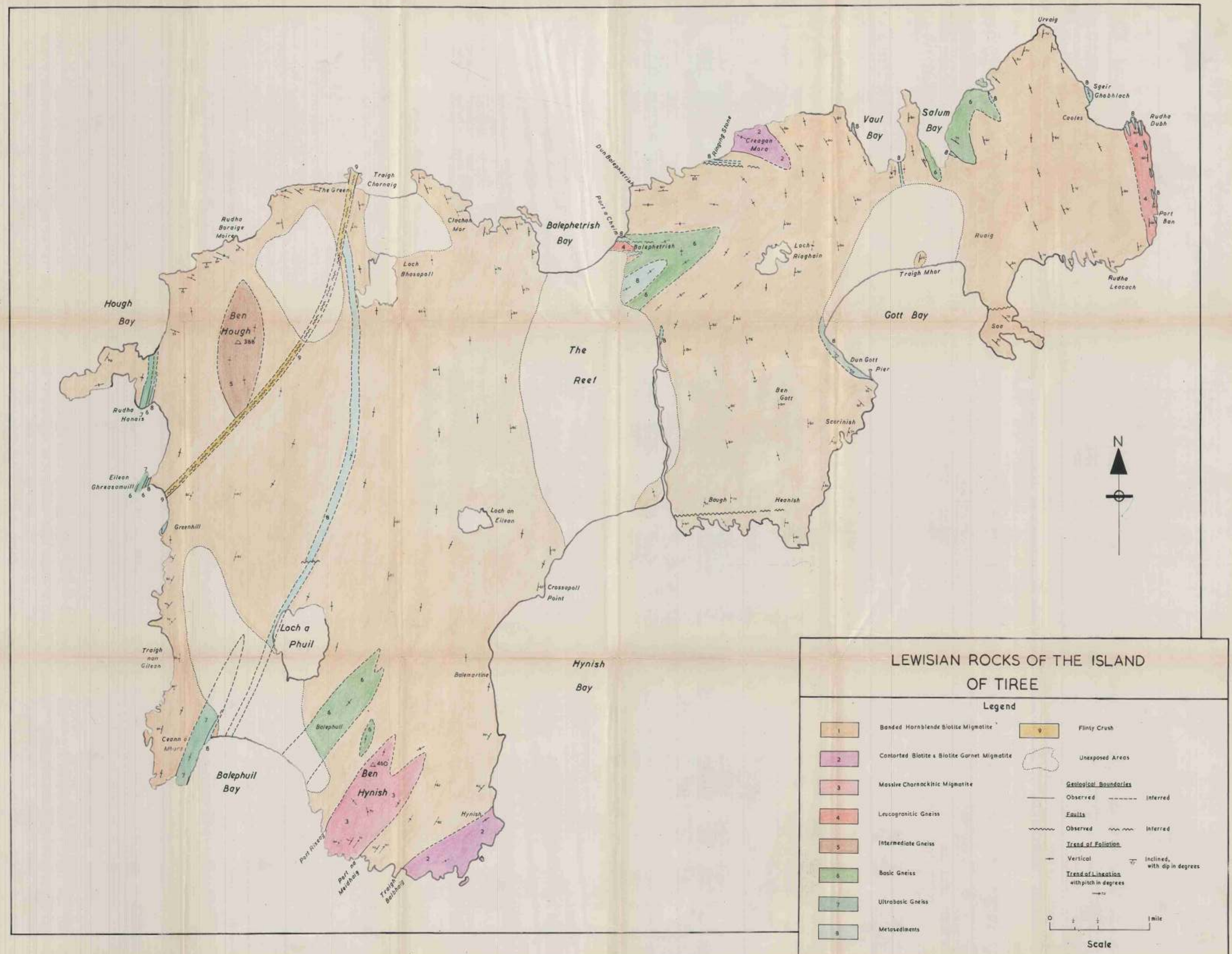
LEWISIAN ROCKS OF THE ISLAND OF TIREE
Legend
1 Banded Hornblende Biotite Migmatite
2 Contorted Biotite & Biotite Garnet Migmatite
3 Massive Charnockitic Migmatite
4 Leucogranitic Gneiss
5 Intermediate Gneiss
6 Basic Gneiss
7 Ultrabasic Gneiss
8 Metasediments
9 Flinty Crush
Unexposed Areas
Geological Boundaries
Observed
Inferred
Faults
Observed
Inferred
Trend of Foliation
Vertical
Inclined, with dip in degrees
Trend of Lineation with pitch in degrees
0
1 mile
Scale
N
Hough Bay
Rudha Honais
Eilean Ghreasamuill
Greenhill
Traigh nan Gilean
Ceann a Mhara
Balephuil Bay
Ben Hough
Rudha Boraige Moire
The Green
Traigh Chornaig
Clachan Mor
Loch Bhasapoll
Loch a Phuil
Balephuil
Ben Hynish
Port Rinsaig
Port na Meidhaig
Traigh Bhàigh
Hynish
Balemartine
Hynish Bay
Crossapoll Point
Loch an Eilean
The Reef
Balephetrish Bay
Port a Chaim
Dun Balephetrish
Balephetrish
Ringing Stone
Creagan Mora
Loch Riaghain
Ben Gott
Baugh
Heanish
Scarinish
Dun Gott
Pier
Gott Bay
Traigh Mhor
Vaul Bay
Salum Bay
Ruaig
Soa
Urvaig
Sgeir Ghobhlach
Caoles
Rudha Dubh
Port Ban
Rudha Leacach